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PERFORMANCE OF SMALL THRUSTERS AND PROPULSION SYSTEMS

by

Thomas E. Saunders

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Thesis Advisor: A. J. Healey

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Performance of Small Thrusters and Propulsion Systems

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ABSTRACT

Performance tests of the longitudinal and lateral propulsion devices for use on the Naval Postgraduate School (NPS) Autonomous Underwater Vehicle (AUV) II are presented. The propulsion requirements for the AUV are discussed and a brief review of the theoretical performance of propulsors is presented. The test procedures used to determine the operating range characteristics of the candidate propulsion devices are described and the results are compared with those obtained theoretically as well as with the parameters of large marine propulsion systems. The results of simulations of longitudinal motion using a non-linear model of the AUV are documented, providing an initial estimate of vehicle acceleration/deceleration performance.

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I. INTRODUCTION

A. BACKGROUND

The Naval Postgraduate School (NPS) has been involved in research activities with Autonomous Underwater Vehicles (AUVs) since 1987, under the technical sponsorship of the Naval Surface Weapons Center, White Oak, Maryland. The research has centered on the development of mission planning, guidance, and control software for use in AUVs, which is of critical importance in current Navy planning. However, actual vehicle trials have always been the true test of any algorithm in order to confirm the results of laboratory simulation.

To date, two AUVs have been designed in conjunction with the project. The first, AUV I, was designed to operate in a test tank (4' x 4' x 40') and was accordingly limited in its size. Its computational capability resided in an IBM AT-clone digital computer positioned alongside the test tank, with commands being transmitted via radio signals and vehicle sensor data fed back to the computer by an umbilical [Ref. 1]. This vehicle, due to the size of the testing facility as well as limited on-board sensors, was restricted to autonomous maneuvers in the vertical plane.

The second AUV, the construction of which is nearing completion, was a necessary and logical follow-on to the first. It was designed to be completely autonomous, with no umbilicals required for the completion of its mission. As its intended operating area is the NPS swimming pool, the vehicle will be capable of verifying control software in the horizontal

as well as vertical planes. In addition, AUV II was designed to have full hovering capability. While a significant activity has been started in the development of advanced autopilots [Refs. 2, 3] and vehicle dynamic modeling—at least based on NPS AUV I [Ref. 4]—it will be the NPS AUV II testbed vehicle that will provide the basis for further investigations of vehicle dynamic modeling and advanced controls performance.

One area not addressed in previous literature, to our knowledge, deals with the design and performance of small thrusters that are needed to provide both main propulsion and positioning thrust for small AUVs of the type contemplated for NPS AUV II. A study of literature has indicated that the performance of larger thrusters as used for off-shore vessel dynamic positioning [Ref. 5], for tanker bow thruster operations [Ref. 6], or for smaller vehicles such as the U.S. Navy's DSRV [Ref. 7] are available, but with propellers of less than approximately nine inches in diameter, information as to the thrust capability is apparently nonexistent in the open literature.

The design of the small AUVs cannot proceed without some verification of scaling rules applied to small thrusters. This thesis will investigate this matter.

B. SPECIFIC OBJECTIVES OF THIS THESIS

The objectives of this thesis were threefold:

1. Test various longitudinal and lateral propulsion designs and prove or disprove their ability to produce sufficient static thrust.

2. Compare the small thrusters as designed for use on AUV II with those currently used in industry on much larger vessels to determine any similarities in performance.

3. Obtain an idea of actual vehicle performance in acceleration and deceleration maneuvers by incorporating the propulsion test results into a computer simulation model of the vehicle.

C. METHOD OF APPROACH

A specific plan was used to complete the objectives of this thesis. First, the propulsion requirements for the vehicle were approximated, as were the design and construction of candidate propulsion devices to meet these requirements. This work is outlined in Chapter II. Chapter III discusses the apparatus used to test the candidate propulsors as well as problems encountered during the testing. Chapter IV details the results of the testing of the propulsors and compares the experimental results with data available for larger propulsion units. Last, Chapter V discusses the results of computer simulations to obtain an approximation of vehicle acceleration/deceleration performance. Although the actual vehicle has yet to operate in water, the propulsion units have been verified to be sufficient to allow AUV II to achieve design performance.

II. PROPULSION SYSTEMS DESIGN CONSIDERATIONS

As AUV II was conceived to be a larger and more complex platform than AUV I with planned missions including more than a simple diving maneuver, a scaling-up of the smaller vehicle's propulsion system was not adequate. The desire for the vehicle to be capable of controlled hovering dictated that the propulsion system should be not only sufficiently powerful but also responsive and reliable.

A. BASIC REQUIREMENTS

At the outset of the design of AUV II, certain performance parameters were decided upon which determined the vehicle's characteristics. Because the vehicle's primary operating area will be the NPS swimming pool (60' x 120'), a 20-foot depth capability was sufficient. In addition, maneuverability was considered of greater value than a high cruising speed. A design target of a nominal cruising speed of two feet per second and the capability to stop from this speed in two vehicle lengths (approximately 12 feet) were established as goals for the investigation of positioning control. With vehicle weight at about 400 pounds, this meant deceleration at 167 feet per second^2 with a maximum thrust level of about two pounds [Ref. 1]. For this reason, initial concern pertained to the design of the stern propulsor.

B. THEORY OF PROPELLER OPERATION

Early propeller theory followed two independent lines of thought: (1) the momentum theory, in which the thrust is explained based on the momentum changes taking place in the fluid, and (2) the blade-element theory, in which the propeller thrust is developed by analyzing the forces acting on various sections of the propeller blades and then integrating over the propeller radius [Ref. 8]. A brief review of the momentum theory is presented here because from the resulting relations for propeller thrust can be derived parameters most often used for comparison of propeller and thruster performance, specifically the thrust loading coefficient C_T and the static merit coefficient C.

The momentum propeller theory begins with the following assumptions: (1) the propeller imparts a uniform acceleration to the fluid passing through it, such that thrust is evenly distributed across the disk; (2) the flow is frictionless; and (3) there is an unlimited in-flow of water to the propeller. The first assumption involves a contraction of the water column passing through the propeller disk. As this contraction cannot occur instantaneously at the disk, the acceleration actually occurs outside, spread out over a finite distance in front of and behind the disk. This is illustrated in Figure 2.1 [Ref. 8], where a propeller disk of area A_0 is placed in a flow of uniform velocity V_A.

At station 1, the velocity of the flow is V_A and the pressure is p_1. At station 2 (the propeller disk), the velocity of the flow has been increased by a factor of $(1 + a)$ due to the uniform acceleration assumption. In

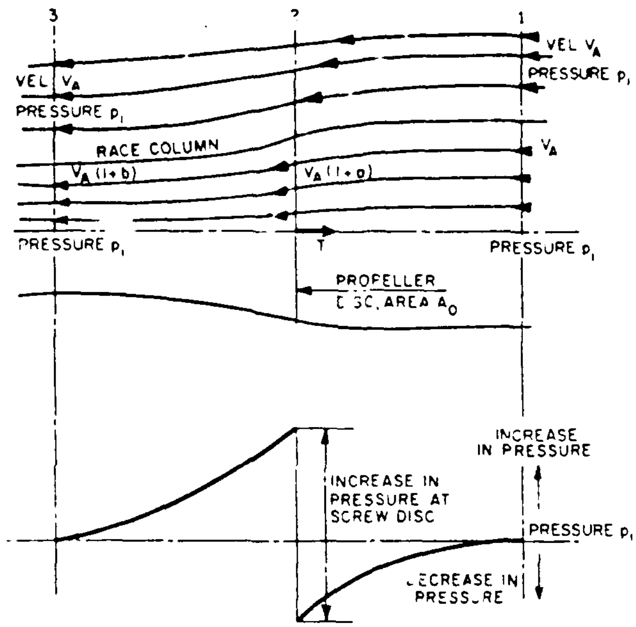

Figure 2.1. **Pressure, Velocity Changes at the Propeller Disk**

addition, the flow decreases in pressure consistent with Bernoulli's law. Upon passing through the disk, the pressure is suddenly increased to a value greater than the ambient pressure p_1. The quantity of water Q passing through the disk per unit time is:

$$Q = V_A(1+a)A_0 \tag{2.1}$$

Thrust T on the propeller disk is equal to the change in momentum per unit time:

$$T = \rho Q[V_A(1+b) - V_A] = \rho Q V_A b \tag{2.2}$$

where ρ is the density of the fluid. The total work done per unit time is equal to the increase in kinetic energy, as friction is neglected [Ref. 8]. This is given by:

$$TV_A(1+\tfrac{b}{2}) \tag{2.3}$$

The increase in kinetic energy is provided by the work done on the fluid by the propeller disk, which is $TV_A(1 + a)$ per unit time. Therefore:

$$TV_A(1+a) = TV_A(1+\tfrac{b}{2}) \quad \text{or} \quad a = \tfrac{b}{2} \tag{2.4}$$

The ideal efficiency η_I is equal to:

$$\begin{aligned} &= \frac{\text{useful work obtained per unit time}}{\text{work expended per unit time}} \\ &= \frac{TV_A}{TV_A(1+a)} \\ &= \frac{1}{(1+a)} \end{aligned} \tag{2.5}$$

If the thrust loading coefficient is defined as:

$$C_T = \frac{T}{(0.5)\rho A_0 (V_A)^2} \tag{2.6}$$

then the efficiency η_I can be redefined as:

$$\eta_I = \frac{2}{1+(C_T+1)^{0.5}} \tag{2.7}$$

Thrust horsepower P_T is equal to the power delivered to the fluid by the propeller disk:

$$P_T = \frac{\text{useful work obtained per time}}{\text{ideal efficiency}}$$

$$= \frac{\frac{(TV_A)}{2}}{1+(C_T+1)^{0.5}} \tag{2.8}$$

When the speed of advance of the propeller is zero, the efficiency is also zero, but the propeller still produces thrust and absorbs power. The relations obtained from the momentum propeller theory can be used to derive a relation for measuring the relative thrusting capability of propellers at zero speed of advance: the static merit coefficient C.

From equation 2.8, it can be seen that when the speed of advance is small, the thrust loading coefficient C_T is very large in comparison to unity. Therefore, equation 2.8 can be rewritten, approximately, as:

$$P_T = (T)(V_A)(0.5)(C_T)^{0.5} \tag{2.9}$$

Substituting equation 2.6 for C_T results in:

$$\text{Static Merit Coefficient } C = \frac{T}{P_T} \cdot \frac{(T)^{0.5}}{(A_0)^{0.5}} \tag{2.10}$$

The maximum value of C for an ideal open propeller is $\sqrt{2}$ and for an ideal ducted propeller is 2. Actual values for propellers in each case are significantly lower. As the experimental data presented in this thesis was obtained at the static or "bollard-pull" condition, the static merit coefficient is the primary parameter for comparing the AUV II propulsors with the much larger marine propulsors. [Ref. 8]

To better predict the results to be obtained from the static propulsion tests, additional relations need to be reviewed. From dimensional analysis, it can be determined that propeller thrust T is proportional to the product (propeller speed n)^2 (propeller diameter D)^4. Additionally, the torque generated by the propeller is proportional to the product $(n)^2$ $(D)^5$. Further, for DC electric motors (which are the prime movers selected for AUV II, as detailed in Chapter III), torque is proportional to the electrical current applied to the motor armature [Refs. 8, 9]. It was therefore expected that the test results would show that propeller thrust T varies with the square of shaft rpm as well as linearly with the current applied to the electric motor.

C. STERN PROPULSOR

1. Motors Selection

Because of the prompt response and reliability of the electric motors of the AUV I propulsion system, similar motors were selected for the main propulsion in the second vehicle. The AUV I had used two Pittman 9513 series 12 volt DC motors, with each motor powering a single shaft by direct drive. A system using two of these same motors per shaft, with the motors ganged together through a belt-drive coupling, was initially chosen to power AUV II. This system, designed for use on large radio-controlled submarine models, allowed two motors to power a single shaft directly through the cogged-belt drive. As shown later in the testing results, this system was capable of producing the requisite one pound of thrust per shaft only at the high end of the motors' operating range, and

was accompanied by serious heating of the motors. For this reason, other motors were selected for the final testing and installation.

The second set of motors used were Pittman series 14202 24 volt DC motors. These motors, with one motor coupled directly to each shaft, provided more torque at a lower voltage and were therefore better suited to continuous operation than were two of the smaller units. The relative sizes of the Pittman motors can be seen in Figure 2.2. The speed versus torque curves for both the Pittman series 9513 and the series 14202 motors are shown in Figure 2.3 [Ref. 10]. As can be seen, the series 14202 produces seven times the torque of the series 9513 for the same rotation speed.

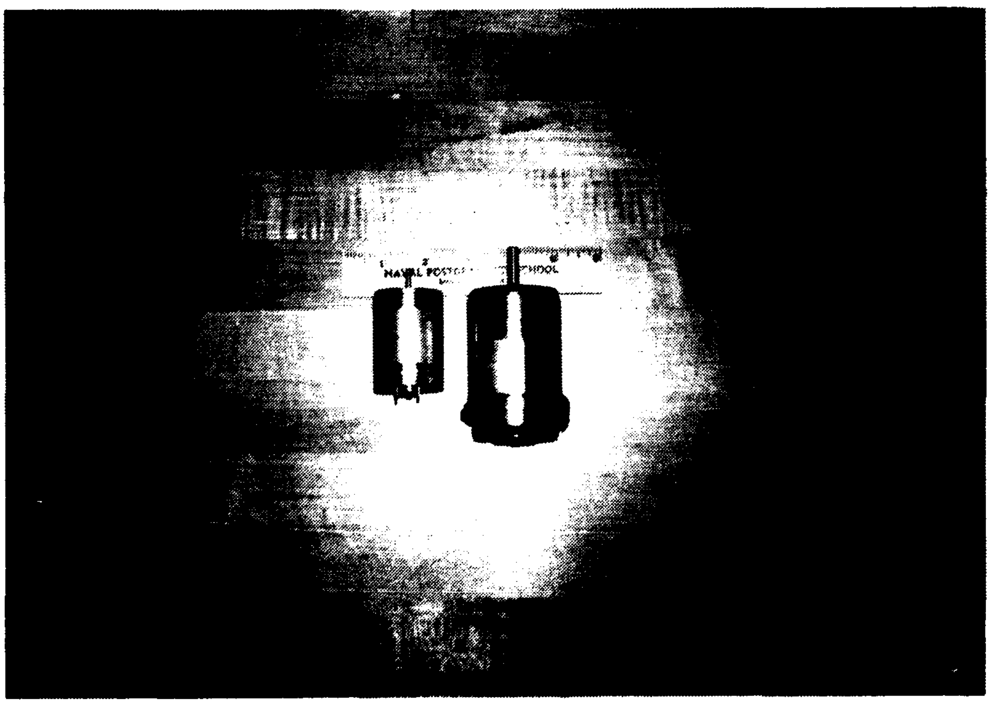

Figure 2.2. **Pittman Electric Motors**

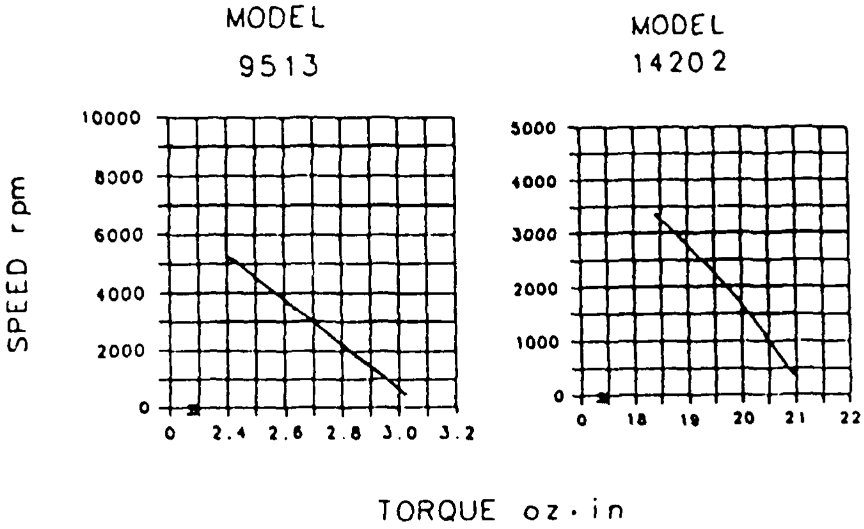

Figure 2.3. **Torque vs. Speed for Pittman Series 9513 and 14202 Motors**

2. Propeller Selection

The two propellers initially selected for evaluation with the vehicle were three-inch-diameter, four-bladed brass units used to power submarine models.[1] Preliminary testing with these propellers showed them incapable of easily providing the design value of one pound of thrust per shaft. For that reason, four-inch-diameter propellers of the same general design (as seen in Figure 2.4) were obtained. These units proved acceptable, with a better load match to the larger Pittman motors, as the later discussion of test results will show.

[1] 32nd Parallel Gato/Balao Running Hardware Kit #07-100.

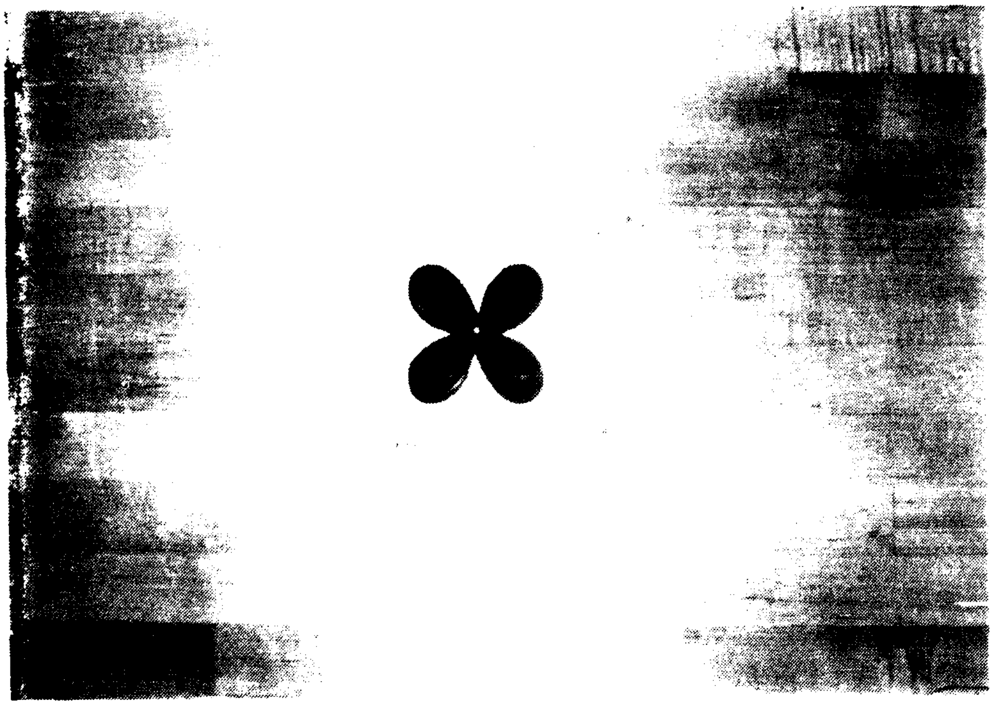

Figure 2.4. **Four-Inch Stern Propeller**

3. Nozzle Considerations

Modifications to the open propeller design were investigated to increase the efficiency and overall thrust. Ducting around an open marine propeller has long been proposed as a means of increasing effective thrust, especially where large thrust at relatively low speed is necessary. A specific type of ducting is the Kort nozzle, introduced in 1933. It consists of a shroud or ring positioned around the propeller and fastened to the hull of the vessel [Ref. 8]. As shown in Figure 2.5 [Ref. 8], the longitudinal section of the ring has an airfoil shape, with the ratio of nozzle length (l) to screw diameter (D) varying according to the speed of the vessel on which it will be used. The nozzle's primary advantage is its ability to increase the static thrust of a propeller by as much as 30 to 40

percent of its open condition. However, as vehicle speed increases, the drag inherent with the ring exacts its toll on vehicle speed.

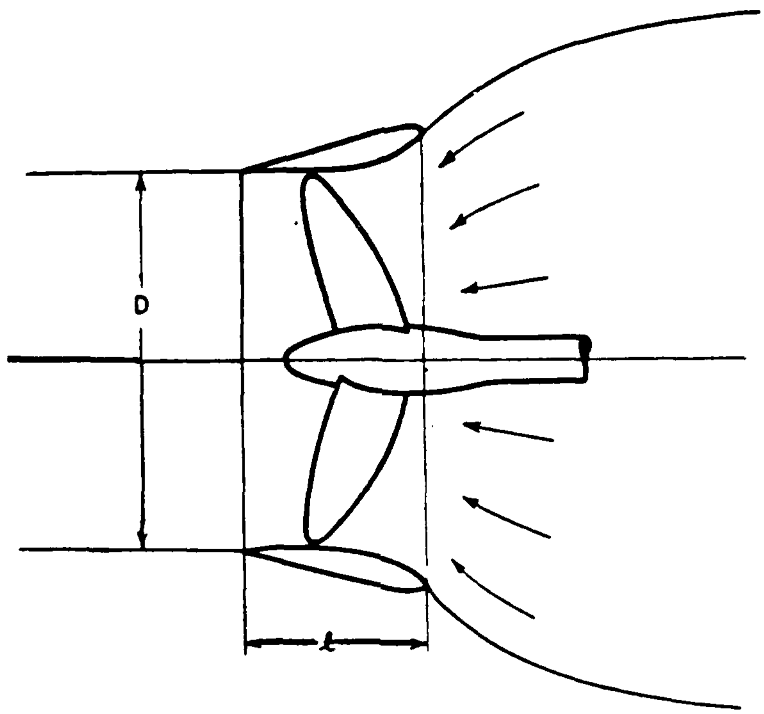

Figure 2.5. **Kort Nozzle**

As the nozzle's entrance is larger than the diameter of the propeller, it increases the *effective* diameter, allowing the propeller/nozzle unit to act on a greater quantity of water than an open propeller. Thus, for the same thrust, a larger mass of water is given a smaller acceleration, resulting in an overall increase in efficiency. Additionally, because the clearance between the propeller blades and the ring is small (ideally, about .1 to .01 inch), blade tip losses are significantly reduced. Much testing has been done to determine optimum nozzle sizes and shapes. Van Manen at the Netherlands Ship Model Basin conducted a series of

experiments with a variety of nozzles and propellers [Refs. 5, 8]. He determined that (1) the optimum nozzle length-to-propeller diameter ratio was about 0.5, (2) the chord of the duct's foil cross-section should make an angle of approximately 10 degrees with the shaft center line, and (3) for B-series screws (such as the AUV II screw), a nozzle increases the effective diameter of the screw by about 10 percent. Additionally, van Manen characterized the usefulness of a Kort nozzle in terms of the value of the Taylor propeller coefficient B_p, where:

$$B_p = \frac{n(P_D)^{\frac{1}{2}}}{(V_A)^{2.5}} \tag{2.11}$$

n	=	propeller speed
V_A	=	speed of advance in knots
P_D	=	delivered horsepower at propeller

These guidelines are as follows:

B_p = 10 to 13	use not advisable
B_p = 20 to 33	use should be considered
B_p = 40 to 60	well worth consideration
$B_p \geq 100$	should use

Based on the design vehicle cruise speed of two feet per second, with estimates of P_D of 0.02 horsepower and propeller speed of 350 rpm, the B_p for the AUV II propulsion system with the large Pittman motors is approximately 33 in the region where use of the nozzle is advised.

In the application of theory to the AUV, some efficiency was lost in a trade-off with ease of construction. To preclude a complicated

fiberglass or metal fabrication, a section of schedule 40 Plexiglas tube was used as the basis for the nozzle, with an overall length of two inches, to approximate the theoretical L/D of 0.5. The nozzle/propeller unit is shown in Figure 2.6. The leading and trailing edges of the nozzle were tapered to approximate as closely as possible an airfoil shape with a 10-degree angle of the chord with respect to the nozzle center line. In addition, upon inspection it was found that the lengths of the blades from root to tip varied on each propeller by as much as .125 inch. This caused the tip clearance between the blades and the nozzle inner surface to vary from approximately .01 to .125 inch. As tip clearance is a major factor in nozzle efficiency, experimental results were expected to be somewhat less than the theoretical increase over open propellers of 30 to 40 percent.

Figure 2.6. **Kort Nozzle Applied to AUV II Propeller**

D. LATERAL THRUSTER

Due to the desire for a hovering capability with AUV II, lateral propulsion devices which were most effective at low vehicle velocities were added to the overall design of the vehicle. From the outset, some form of a tunnel thruster was deemed as the most likely choice due to their relative simplicity as well as their proven capability in slow-speed maneuvering of surface vessels (bow-thrusters in both Navy and merchant ships) and submersibles (U.S. Navy's DSRVs and NR-1). The complete system would consist of four thrusters total—two vertical and two lateral—with each pair mounted at opposite ends of the vehicle as far from the vehicle center as possible for maximum effect [Ref. 1]. A design specification of one pound of thrust per thruster was established to allow the vehicle adequate low-speed maneuverability. Both iterations of the lateral thruster were designed by David Marco [Ref. 11].

1. Motor Selection

Pittman 9513 series 12-volt electric servo motors were initially selected as the prime mover due to their assumed adequate torque and speed characteristics. One motor was selected to power each thruster unit. Finally, 24-volt DC units were substituted to make up for perceived losses within the thruster ducts which had to be lengthened due to other factors in the overall vehicle design.

2. Duct Design for Tunnel Thruster

One of the primary considerations in the application of a tunnel thruster to a vehicle design is the configuration of the interior of the tunnel and the way the tunnel inlets/outlets fair into the overall design.

With regard to the tunnel's interior shape, several studies, both experimental and theoretical, have been undertaken to determine the most favorable geometry. In the most exhaustive of these studies, Taniguchi tested three basic tunnel shapes: (1) a standard parallel-wall tunnel, (2) a concave wall to maintain a constant flow area in the vicinity of the propeller hub, and (3) a convex wall to examine static pressure recovery in the propeller exhaust. Through an examination of his test results, he determined that a standard parallel-wall tunnel resulted in the most efficient thruster. Thus, a parallel-wall thruster design was selected for AUV II. [Refs. 6, 12]

The diameter of the tunnel for AUV II was selected more on the basis of the availability of commercial components than by design iteration. With vehicle hull dimensions of approximately 10 inches high by 16 inches wide, a tunnel diameter of 3.0 inches was selected based on the availability of 3.0-inch schedule 40 PVC pipe and the desire to make the thruster components as large as possible (for ease of construction) without using an excessive amount of vehicle interior space. However, preliminary calculations using an iterative design approach developed by Beveridge [Ref. 6] show a tunnel diameter of 3.0 inches to be acceptable for a tunnel length of 10 to 16 inches and an overall vehicle length of six feet. This iterative approach consists of (1) the preliminary selection of tunnel diameter (3.0 inches), (2) the selection of an average vehicle turning rate from curves formulated from previous thruster designs (0.7 degrees/second), (3) the calculation of static thrust required to achieve that turning rate (.03 pounds), and (4) the calculation of the propeller speed necessary

to achieve the calculated value of static thrust (170 rpm). Using the Beveridge relations and curves in a different order and starting the iteration with the design value of one pound of static thrust per thruster, a first approximation of vehicle turning rate (eight degrees per second) was obtained.

Of equal concern for the shape and diameter of the tunnel is the design of the inlet/exit lip, where the end of the tunnel fairs to the exterior surface of the vehicle. Because the tunnel thrusters are bi-directional, each tunnel opening acts alternatively as an intake or as an exhaust port. Unfortunately, for maximum efficiency, the inlet is best shaped like a long-radius nozzle, while the exhaust is best shaped as a simple step to assure maximum thrust. The best compromise between the two was determined by Beveridge, where the shape consists of a rounded edge of radius equal to one-tenth the diameter of the tunnel opening with a small step (equal to one-tenth of the lip radius) cut just as the lip fairs into the tunnel wall. This compromise was determined through testing to provide the advantages of each shape to the overall efficiency of the tunnel. [Ref. 6]

3. Power Transmission

The issue of power transmission from the motor to the propeller was, and for small thrusters will remain, a difficult one. To prevent tunnel blockage, all machinery with the exception of the propeller blades should be located outside the tunnel. Barring the use of a small right-angle drive unit, an initial thruster design was proposed in which the propeller blades were inset into the center of a main drive wheel, using a

smooth belt to transmit power from the motor shaft (located parallel to the axis of the tunnel) to the propeller shaft. This system was proven in initial testing to be unsatisfactory. The smooth belt hydroplaned on the propeller shaft at relatively low torques, producing only .25 pounds of thrust at maximum propeller rpm (a quarter of the target value).

The second design, which ultimately proved successful in test, involved power transmission through gears. The propeller bade was built into the spokes of a 3.0-inch-diameter nylon gear placed in the center of the tunnel. The drive motor, placed in a waterproof housing parallel to the tunnel, turned a smaller drive gear which was meshed with the propeller/gear. A gear ratio of 2.5 to 1 allowed the propeller and the motor to operate closer to their individual design speeds. [Ref. 11]

4. Propeller Selection/Design

The selection of the appropriate propeller shape again relied heavily on the research of Beveridge and Taniguchi [Refs. 6, 12]. They found that a Kaplan-shaped propeller bade, because it is wider at the tip than at the root, significantly reduced cavitation. In addition, due to the very slight curve at the tip, the Kaplan blade more easily matched the shape of the tunnel and allowed the very slight clearance necessary for a high thruster efficiency. Eight Kaplan blades were attached to four struts in the propeller disk/gear to produce the completed propeller. The attachment of the blades to the centrally fixed gear eliminated the tip clearance problem (the blades were rotating in unison with the section of tunnel against which they would normally have had to maintain

clearance). Figure 2.7 depicts the propeller blades and their installation within the thruster tunnel.

5. Expected Losses

Prior to the commencement of testing of the lateral thrusters, there were several areas where losses were anticipated. Because the success of the geared power transmission was of primary concern, the tunnel thruster as tested was not optimized. First, no attempt was made to provide a rounded lip/step at the ends of the tunnel. Second, the method of attachment of the propeller blades to their respective support struts was optimized for *structural* rather than *flow* considerations. Last, no attempt was made to decrease the friction of the walls of the tunnel through the application of waxes or polymers. All of these factors serve to decrease the overall efficiency of the thruster unit. However, the eventual achievement of the design thrust goal demonstrated the basic soundness of the design. Improvements remain as the subject of follow-on work.

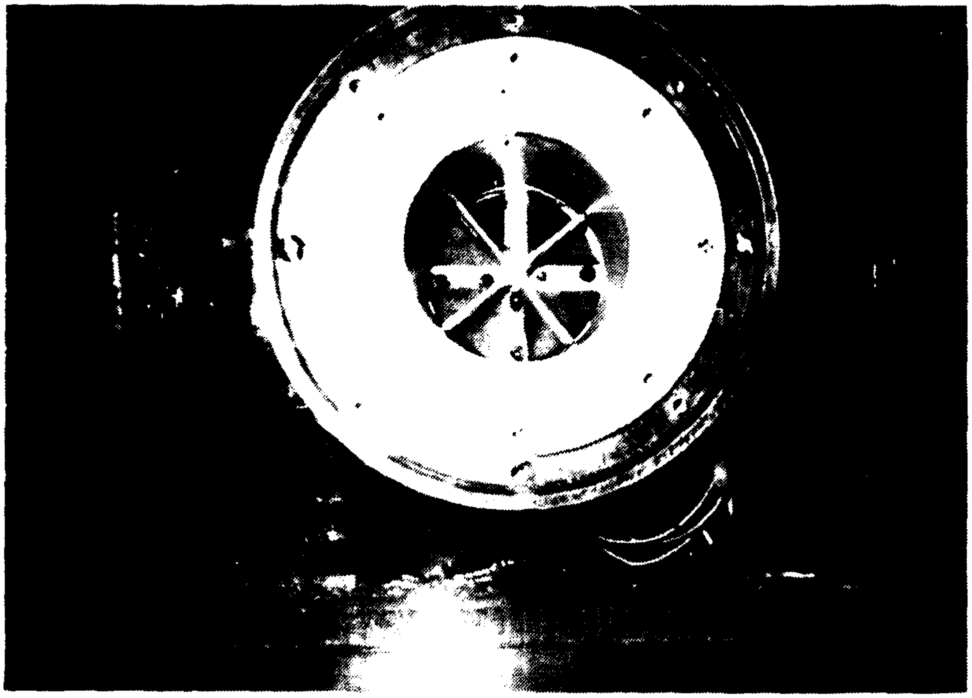

Figure 2.7. **AUV II Tunnel Thruster Propeller**

III. TEST APPARATUS

The testing of the candidate propulsion systems for the AUV was necessary for several reasons. First, a quantitative measure of each of the candidates was considered necessary in order to make a final design decision for the vehicle's propulsion systems. Second, the design of control software and hardware for the vehicle is made easier if characteristics of the systems to be controlled are known (specifically, the variance of thrust with input voltage, current, or motor rpm). Last, it is just good sense to ensure that a particular design meets a stated minimum requirement before expending limited assets to reproduce the design for operational purposes.

A. APPARATUS DESCRIPTION

Because of the relatively small physical size of the AUV, it was decided to test full-scale models of the candidate propulsion systems, measuring specific parameters throughout each system's operating range. Although conventional propulsion testing procedure involves the use of tow tanks to determine a system's true open-water thrust capabilities, it was felt that adequate static or "bollard-pull" results could be obtained through the use of a smaller test enclosure. The enclosure used was a plastic tank with interior dimensions 36.5 inches by 22 inches, filled with water to a depth of approximately 15 inches. The propulsion system to be tested was placed in a watertight Plexiglas box to allow immersion in the test tank. This box was then suspended from a knife-

edge support on an overhead bar by a semi-rigid frame and partially submerged in the tank. The propulsion box assembly was ballasted slightly negative to remove buoyancy components from the thrust measurement. A force transducer capable of measuring up to 10 pounds was placed in parallel with the semi-rigid support frame to react against and measure thrust in either direction. The parameters measured during each test included: (1) input voltage (volts DC), (2) input current (amperes), (3) motor rpm (by optical tachometer), (4) raw transducer data, and (5) filtered transducer readings (millivolts DC). All equipment was set up as shown in Figure 3.1. Figure 3.2 shows a more detailed view of the transducer installation on the semi-rigid support frame. The stern propulsor and tunnel thruster test boxes are shown in Figure 3.3 and 3.4, respectively. Figure 3.5 depicts the installation of the stern propulsor test box in the tank.

B. SYSTEM CALIBRATION

Due to the potential for thrust measurement errors arising from offsets and weight/buoyancy moments between the lines of action of the propulsion devices and the transducer (flexibility of the Plexiglas box, as well as the support frame during large loads), the system was calibrated to determine the transducer response to known load-line thrust throughout the anticipated operating range of the propulsion system. This calibration was accomplished by attaching a line to the Plexiglas housing for the propulsion system such that a tension on the line would closely approximate thrust along the system's line of action. Tension in the line

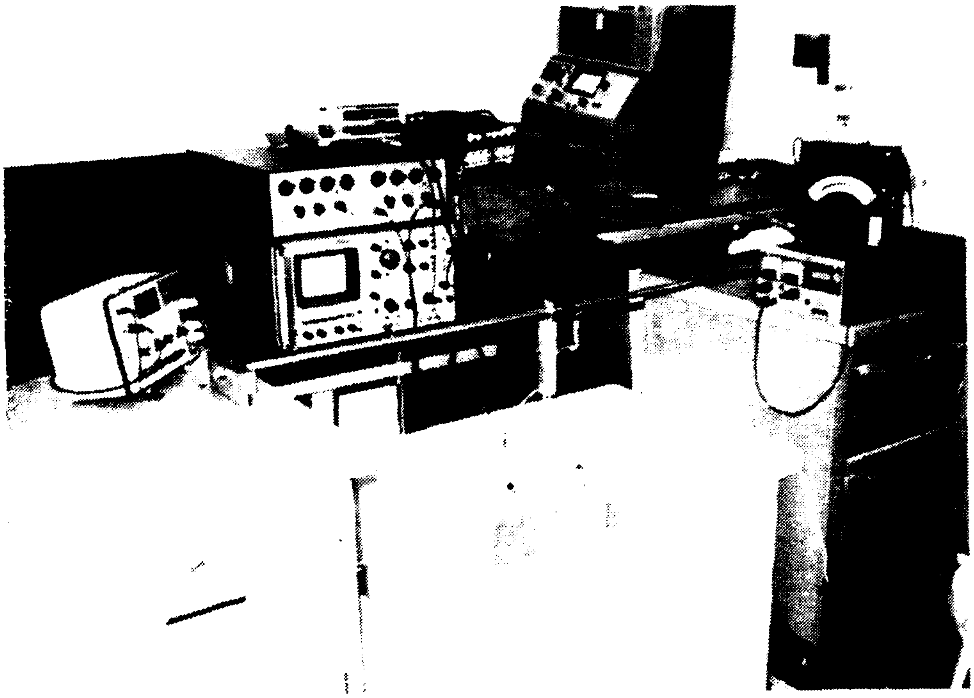

Figure 3.1. **Test Equipment Setup**

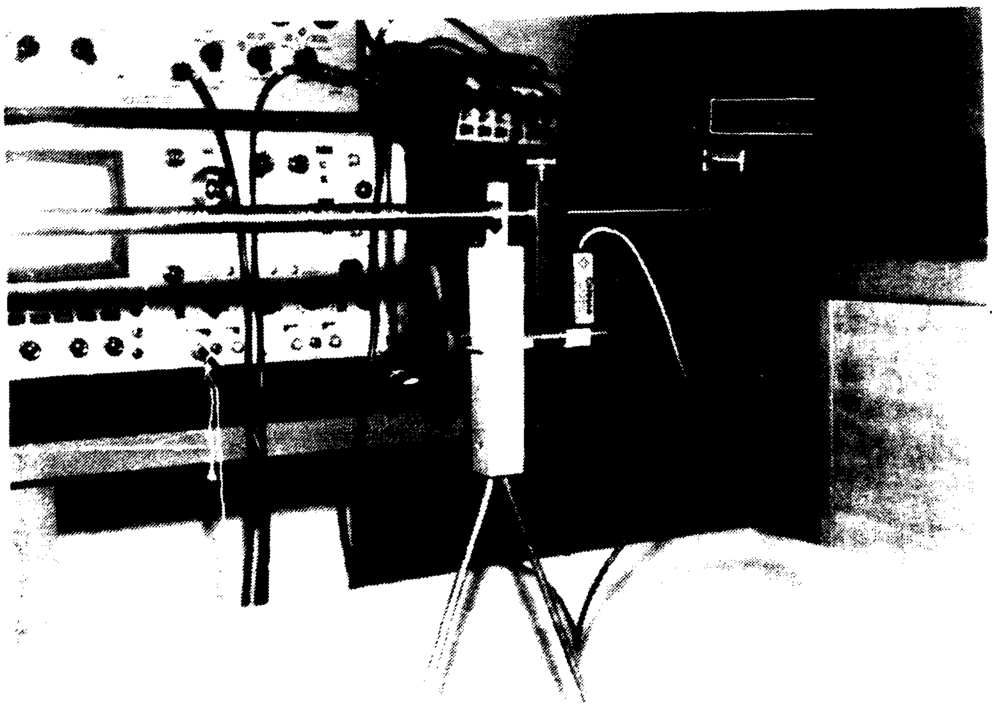

Figure 3.2. **Transducer Installation**

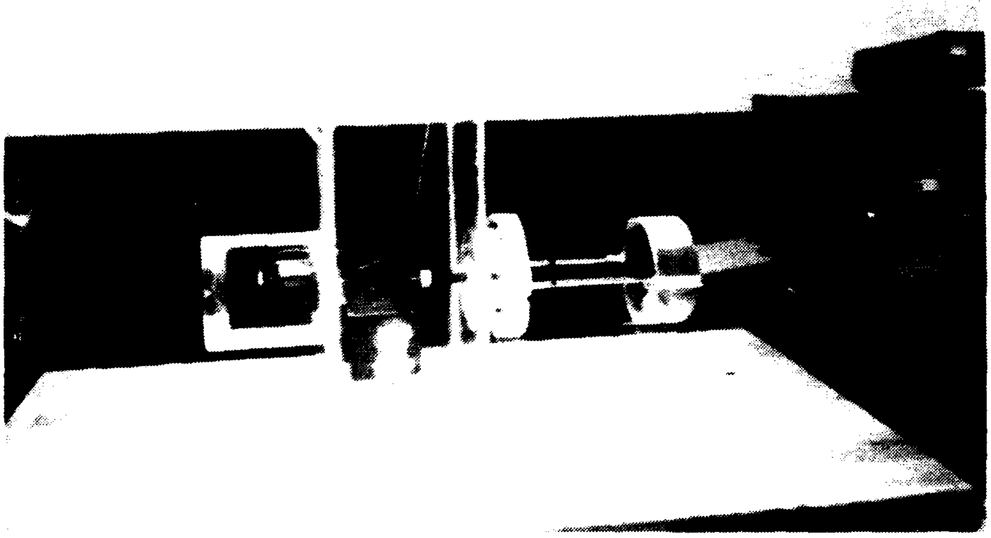

Figure 3.3. **Stern Propulsor Test Box**

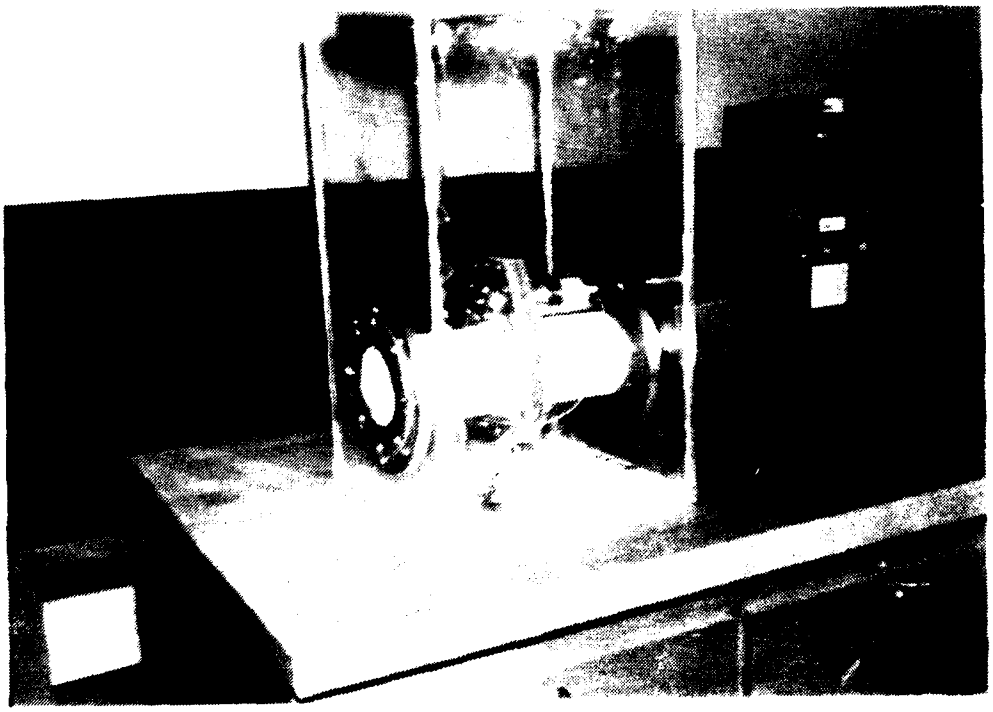

Figure 3.4. **Tunnel Thruster Test Box**

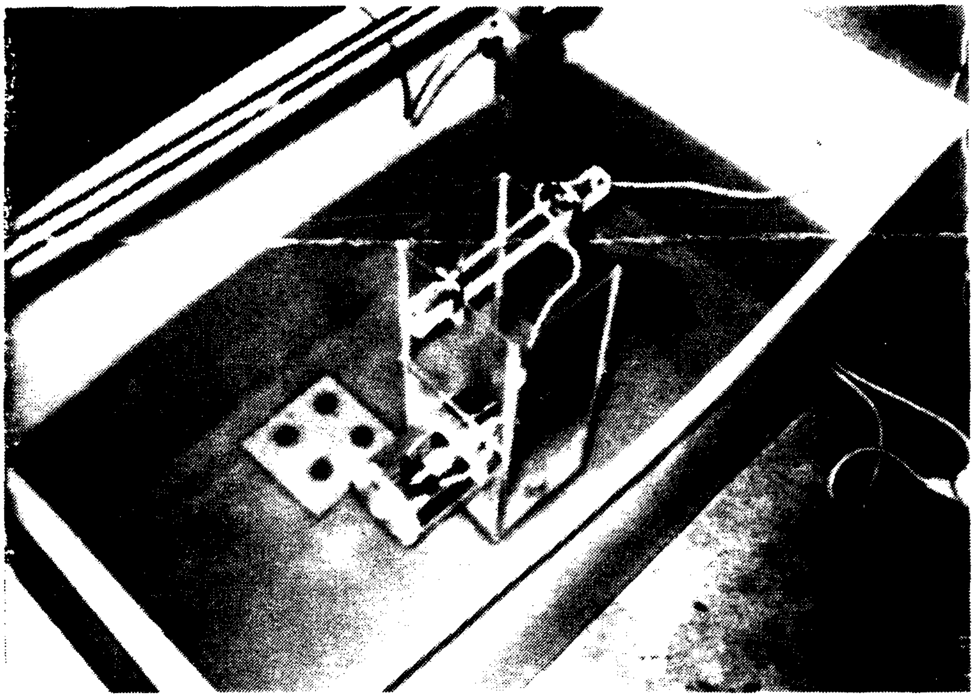

Figure 3.5. **Test Box in Tank**

was created by a system of weights and pulleys. The test apparatus was in the same status during the calibration as was used during the actual tests (ballasted and partially submerged to the same depth). The linear relation between thrust force and transducer reading created through this calibration, as shown in Figure 3.6, was repeatable and accurate to within approximately one-tenth of a pound. Using this calibration line, the transducer readings produced during testing were converted to thrust in pounds of force.

C. TESTING DIFFICULTIES/INACCURACIES

During the course of the propulsion testing, two main problems were noted. First, in testing the stern-mounted propulsors, it was noted that

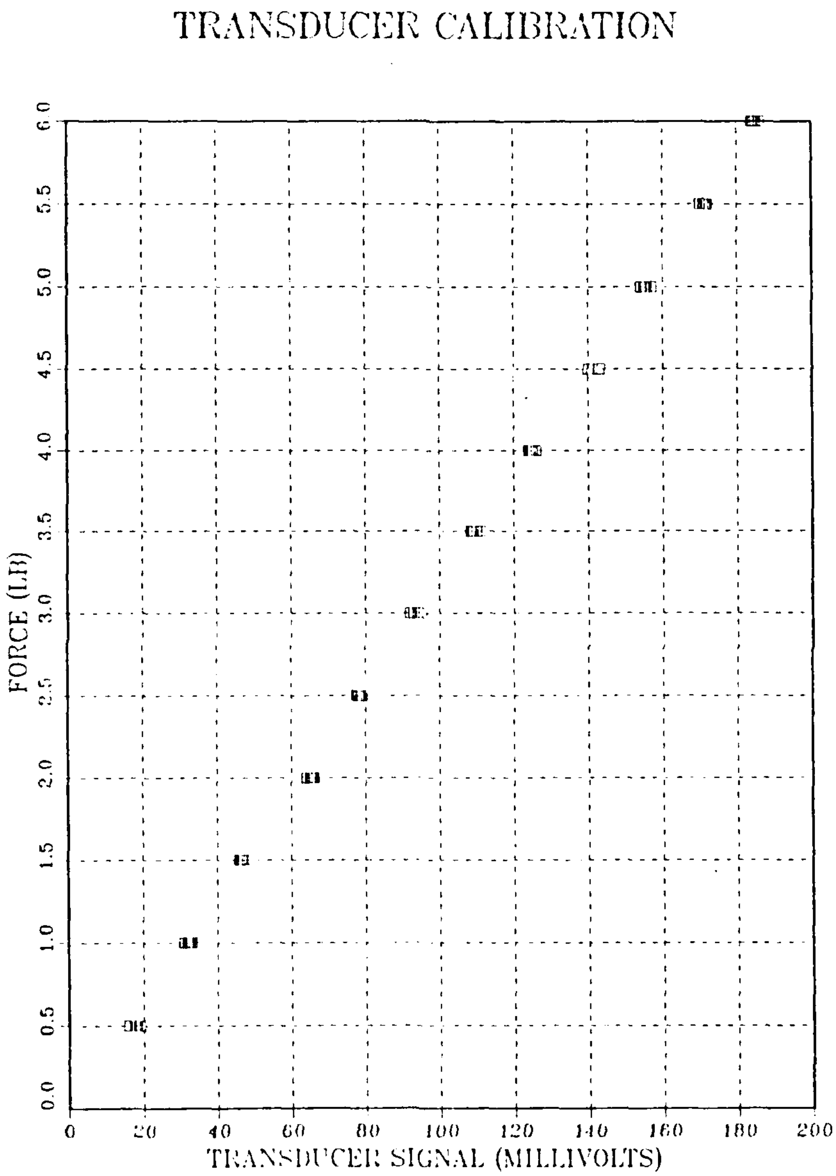

Figure 3.6. **Transducer Calibration**

the flow from the propeller impinged on the containment box– slightly in the case of forward thrust, significantly in the case of astern thrust. This flow caused the box to oscillate about the true thrust value, making it difficult to determine the proper transducer reading, even with filtering. The solution was to place a baffle plate between the box and the propeller during testing to isolate the box (and the transducer) from the effects of the flow.

Second, in the test of all propulsion devices, water flow added some degree of inaccuracy to the final result. Due to the relatively small size of the tank used for the tests, a circulatory flow developed from the exhaust of the propeller disk to the inlet, which increased in severity as the speed of the propeller was increased. The effect of this flow would appear to be to cause the thrust readings to be not at the "bollard-pull" condition but rater at a condition of reduced thrust similar to the propeller having some speed of advance. Because the velocity of the water entering the propeller disk cannot be measured with the current equipment setup, an exact value of static thrust cannot be determined. However, because of the direction of the circulation, the result achieved from the tests with the flow present are likely to be less than the true static thrust values. The errors in the current system are therefore on the conservative side. The solution for this problem would be to use a larger test facility where a circulation such as that described would be less likely to occur. Should additional testing be necessary, it is strongly recommended that such a facility be used.

IV. TEST RESULTS

The importance of preliminary testing of propulsion designs for new vehicle concepts was proven by the results of this project. The results of early testing of both the stern and lateral propulsors had profound effects on the motor and power transmission configurations of the AUV. As a result of the tests, the capabilities and characteristics of the installed devices are now known.

A. STERN PROPULSOR

Four iterations of a stern propulsor were tested: (1) two 12-volt servo motors powering a single shaft with an open, three-inch-diameter propeller, (2) two 12-volt motors with an open, four-inch propeller, (3) one 24-volt servo motor driving an open propeller, and (4) one 24-volt motor driving a propeller enclosed in a Kort-type nozzle. The testing with the open, three-inch propeller lasted only long enough to prove that these propellers, even at maximum revolutions, were incapable of delivering the one pound of thrust calculated as necessary to achieve the vehicle *acceleration-based* design performance parameters (deceleration from a speed of two feet per second to zero in two vehicle lengths) [Ref. 1].

1. Small Motors

Test results with an open, four-inch propeller driven by two 12-volt motors proved that the design value of one pound of thrust per shaft was achievable with the larger propeller. As Figure 4.1 shows, the thrust

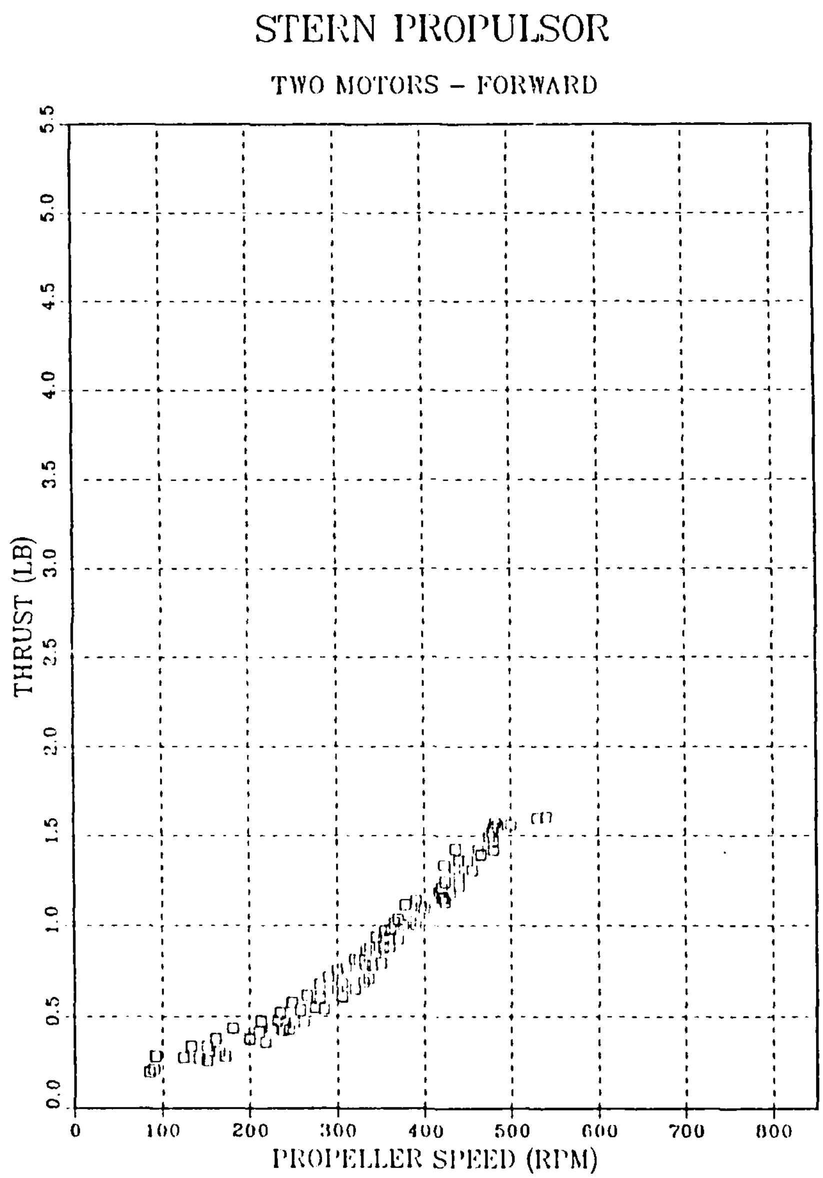

Figure 4.1. **Thrust vs. Rpm, Stern Propulsor (Ganged Motors), Ahead Direction**

force in the ahead direction approximates a variation as the square of the propeller speed. The plot of thrust in the reverse direction (Figure 4.2) verifies that the propeller was more efficient in the ahead direction, especially at higher propeller speeds. At a speed of 450 rpm, the propeller produced nearly 40 percent more thrust in the ahead direction than in the reverse direction. Plots of thrust as a function of voltage input and current applied (Figures 4.3 through 4.6) exhibit a roughly linear correlation in both propeller directions. Although not adequately demonstrated on the plots, the testing of the ganged motors showed that they were incapable of maintaining the desired thrust level continuously for the anticipated vehicle mission length of one hour. After only approximately five minutes of operation at their maximum voltage, the motor casings became extremely hot and the maximum drawn, combined current dropped from nine amps to approximately six amps, with a similar drop in thrust. Because these were permanent magnet servo motors, the magnetic field is thought to have been reduced at the high temperatures. For this reason, the stern propulsion drive was shifted to single, 24-volt motors per shaft.

2. Larger Motors

The second iteration of the stern propulsion system, with each shaft powered by a single, larger motor, produced very satisfactory test results. Not only did the larger motor produce the design value of thrust per shaft (one pound), it achieved that level at approximately one-fourth its rated voltage. The system therefore should have no problem

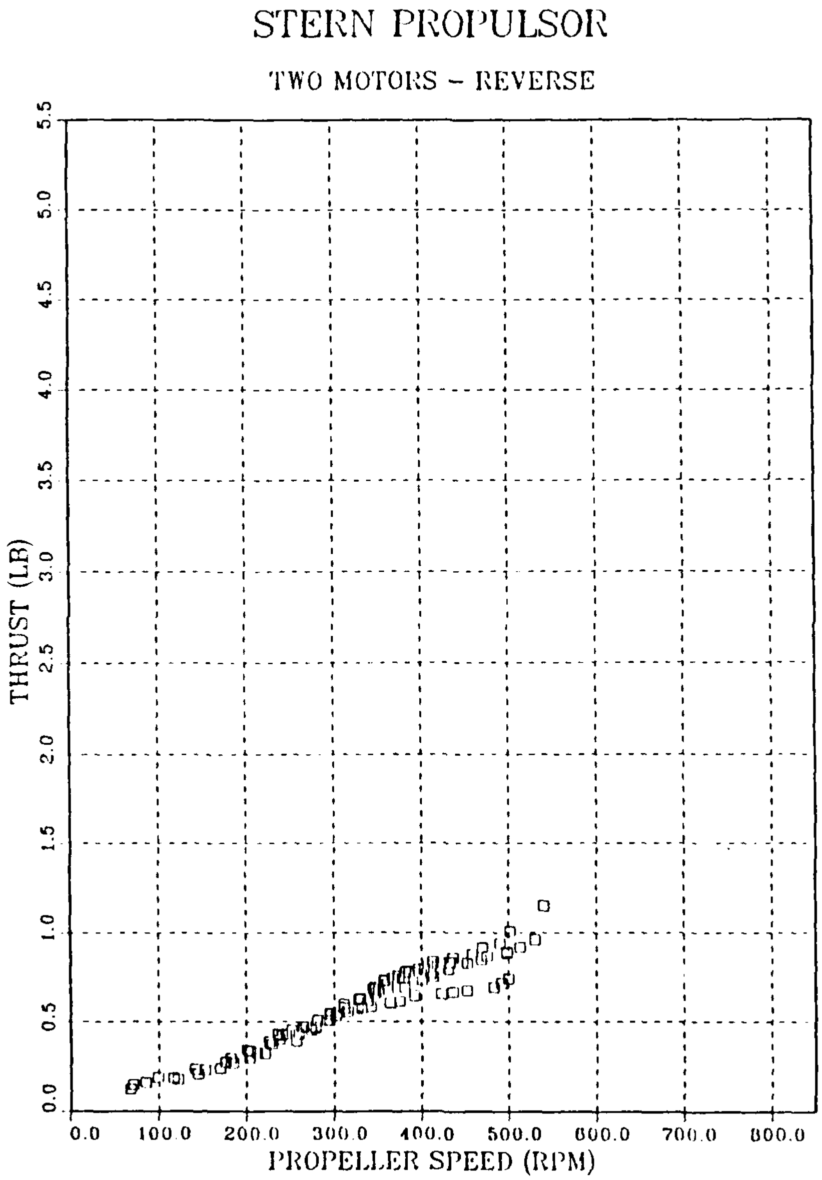

Figure 4.2. **Thrust vs. Rpm, Stern Propulsor (Ganged Motors), Reverse Direction**

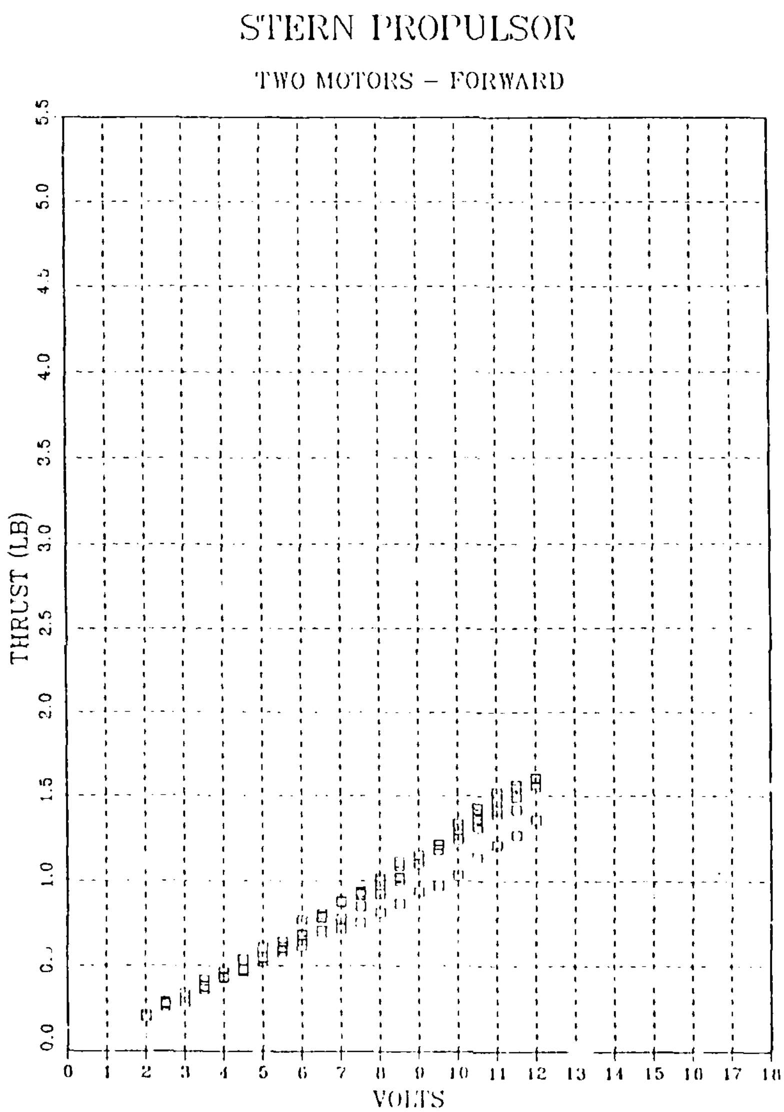

Figure 4.3. **Thrust vs. Voltage, Stern Propulsor (Ganged Motors), Ahead Direction**

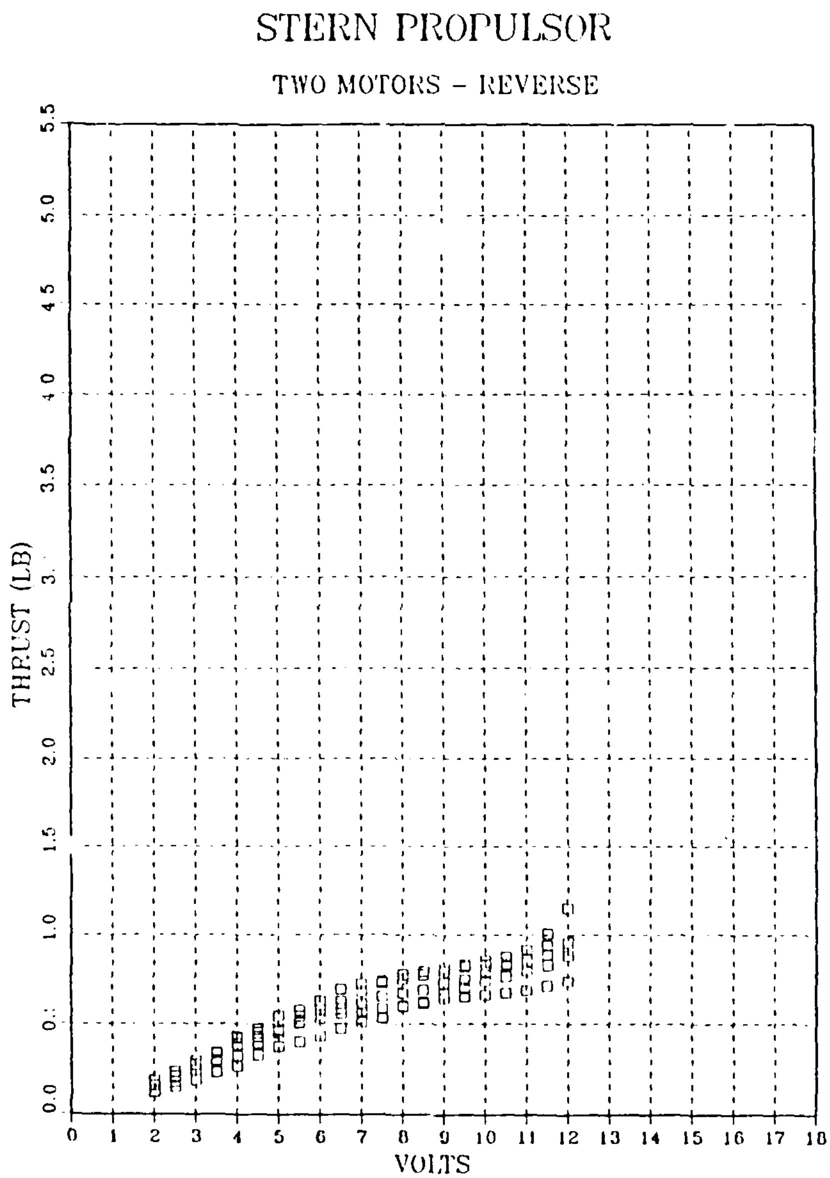

Figure 4.4. **Thrust vs. Voltage, Stern Propulsor (Ganged Motors), Reverse Direction**

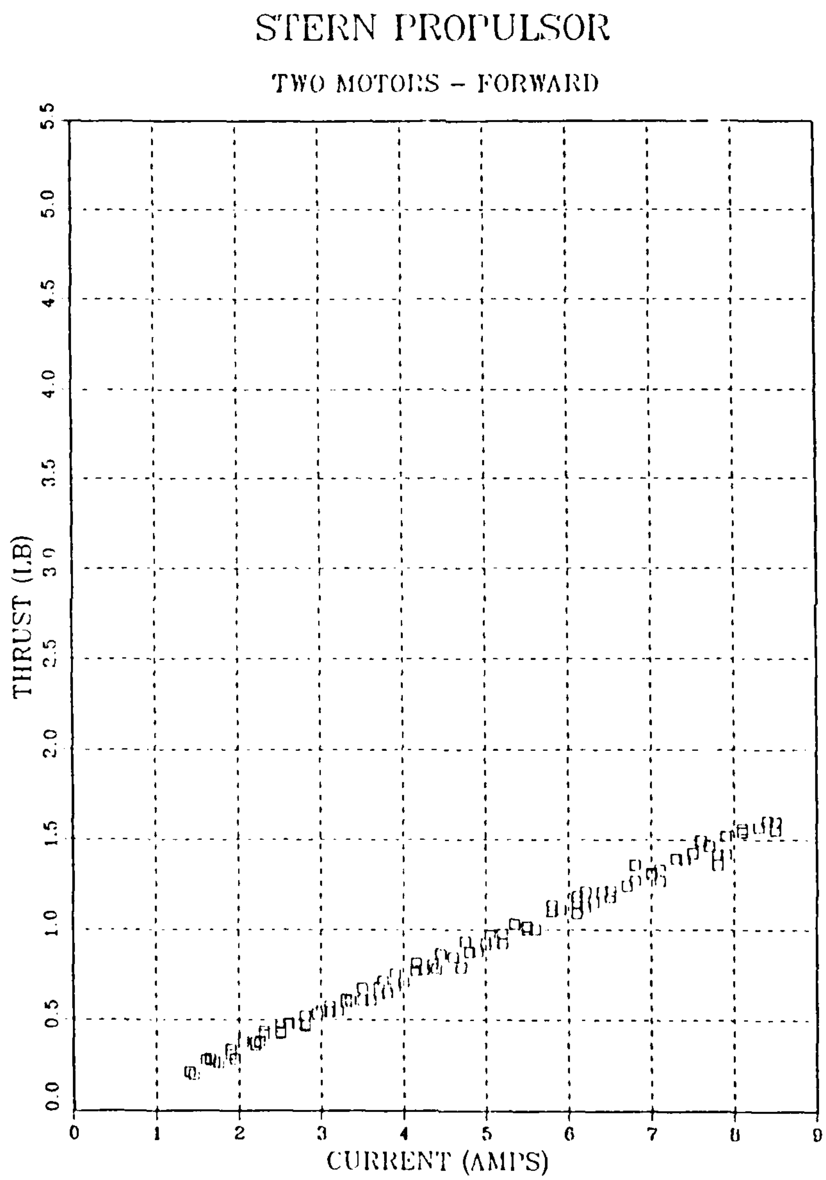

Figure 4.5. **Thrust vs. Current, Stern Propulsor (Ganged Motors), Ahead Direction**

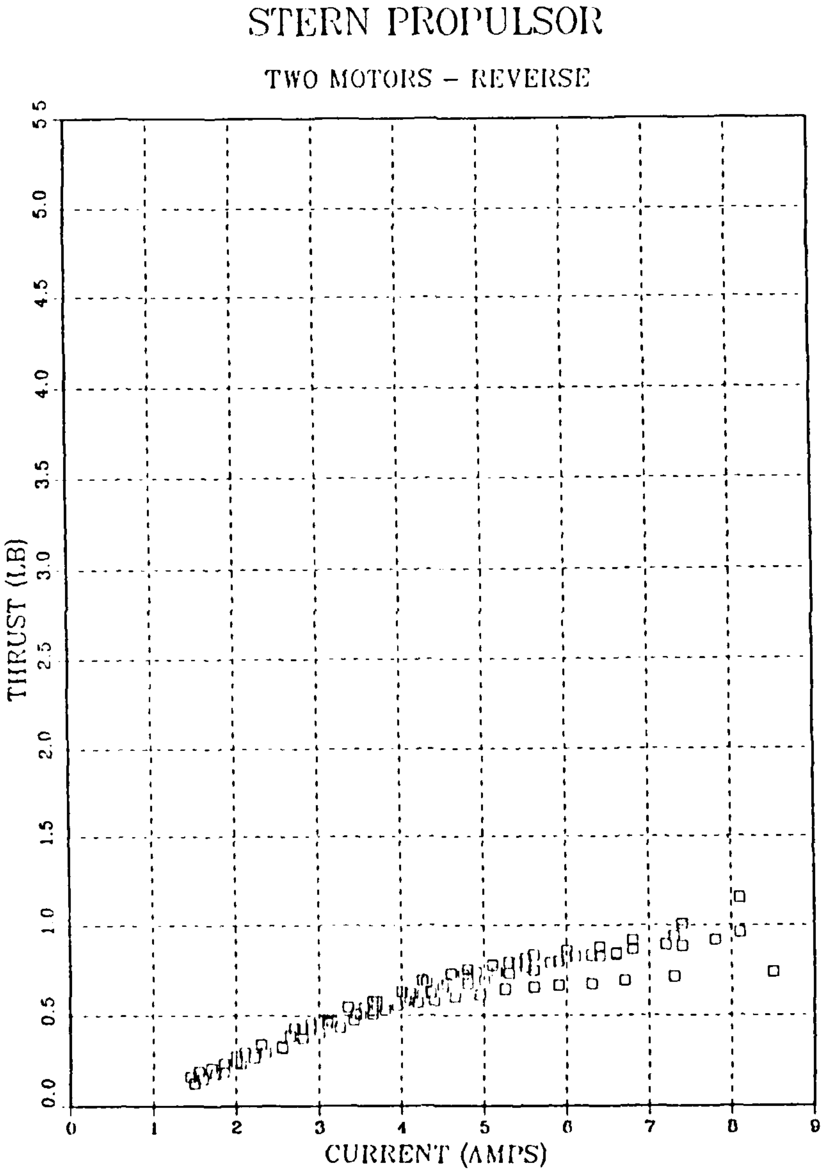

Figure 4.6. **Thrust vs. Current, Stern Propulsor (Ganged Motors), Reverse Direction**

maintaining the design speed of two feet per second for a one-hour period. As can be seen from Figures 4.7 and 4.8, thrust produced varied as a function of the square of propeller speed in both forward and reverse directions. As before with the smaller motors, thrust varied approximately linearly with voltage input and current. This can be seen in Figures 4.9 through 4.12. Data for the large motor is more tightly grouped than that for the small motors. It is believed that the heating of the smaller motors during their testing produced the wider variation in values. The thrust produced varied in direct correlation to the period of time the motor had been operated when the data was recorded. This heating was not present during the testing of the larger motor.

3. Kort Nozzle

The addition of the Kort-type nozzle to the open propeller produced the expected increase in static thrust. As can be seen in Figures 4.13 and 4.14, the propeller/nozzle unit produced nearly five pounds of thrust at its upper limit in the ahead direction, with a similar gain experienced in the reverse direction. The addition of the nozzle allowed the propeller to produce approximately 20 percent more thrust for the same electrical power input to the motor at the upper end of the motor's operating range, as can be seen in Figures 4.14 through 4.18. The gain in efficiency at the low end of the motor's range, where the propulsion system is expected to operate during most of a typical vehicle mission, was also significant (10 percent reduction in the amount of power necessary to generate one pound of thrust per shaft). The gains realized with the

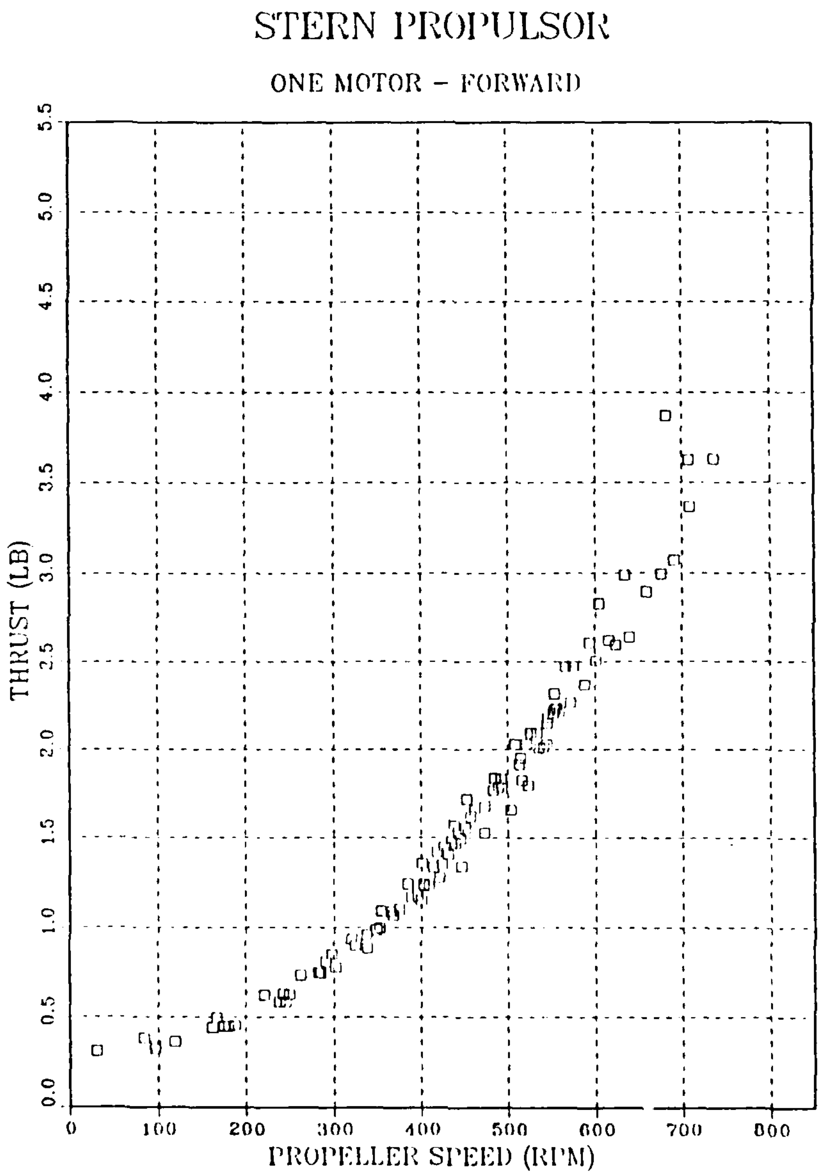

Figure 4.7. **Thrust vs. Rpm, Stern Propulsor (Larger Motor), Ahead Direction**

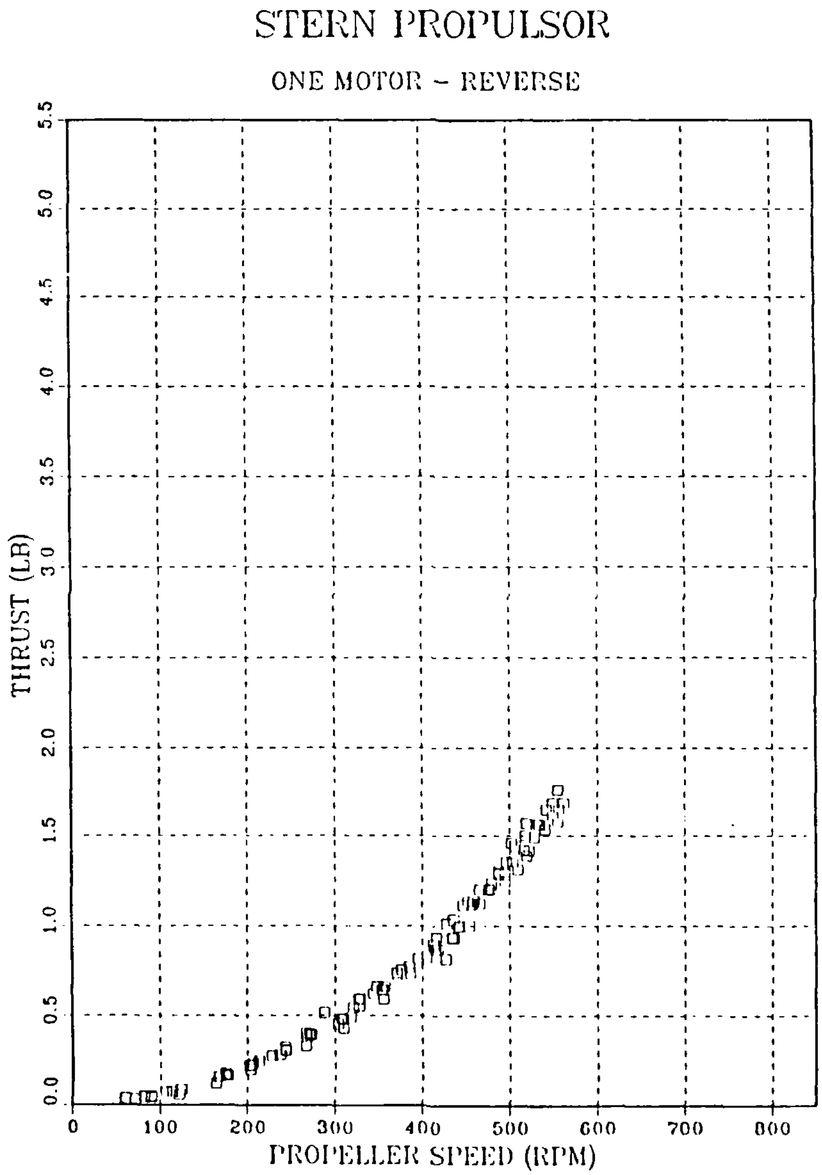

Figure 4.8. **Thrust vs. Rpm, Stern Propulsor (Larger Motor), Reverse Direction**

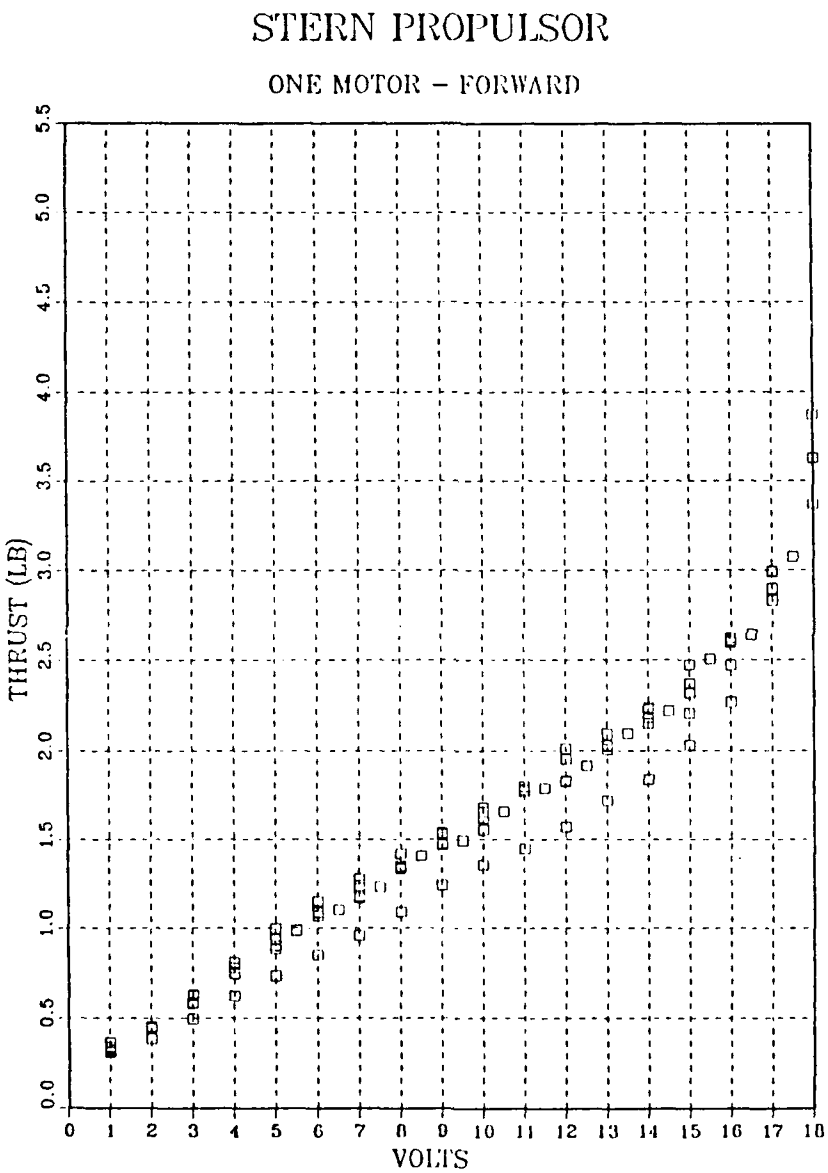

Figure 4.9. **Thrust vs. Voltage, Stern Propulsor (Larger Motor), Ahead Direction**

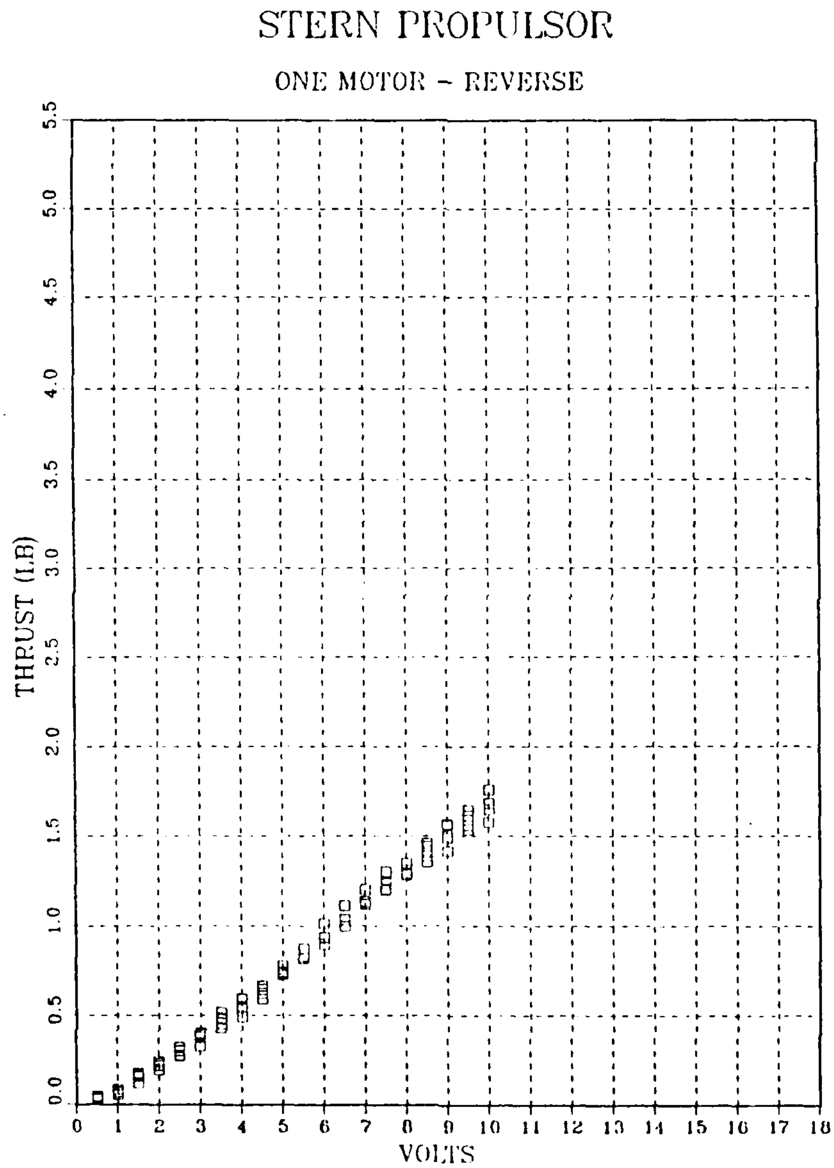

Figure 4.10. **Thrust vs. Voltage, Stern Propulsor (Larger Motor), Reverse Direction**

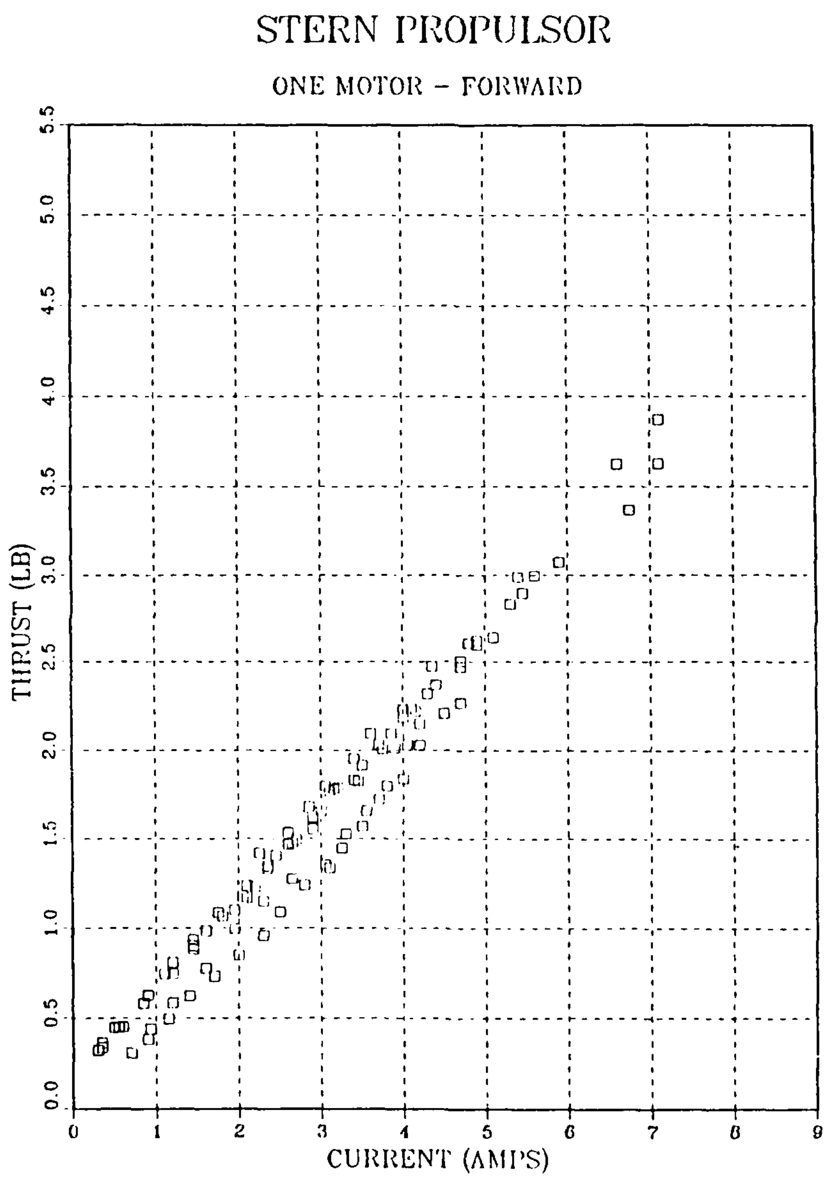

Figure 4.11. **Thrust vs. Current, Stern Propulsor (Larger Motor), Ahead Direction**

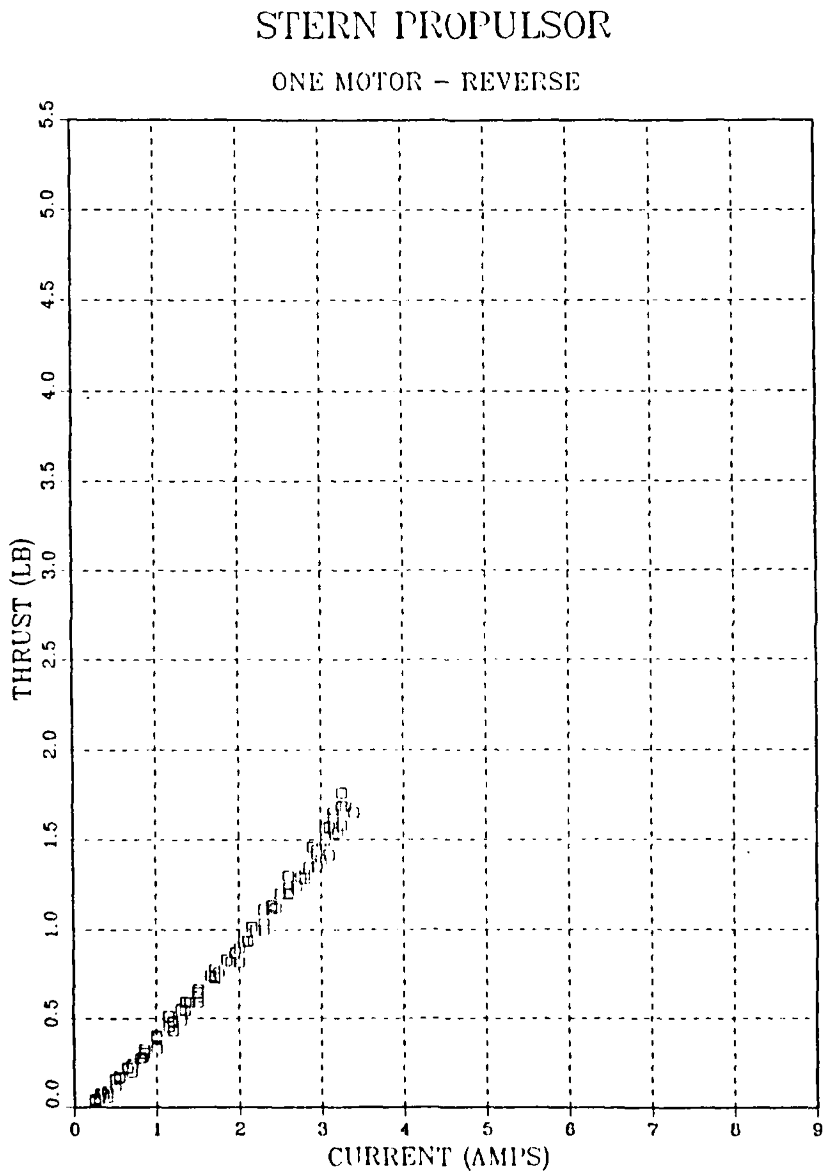

Figure 4.12. **Thrust vs. Current, Stern Propulsor (Larger Motor), Reverse Direction**

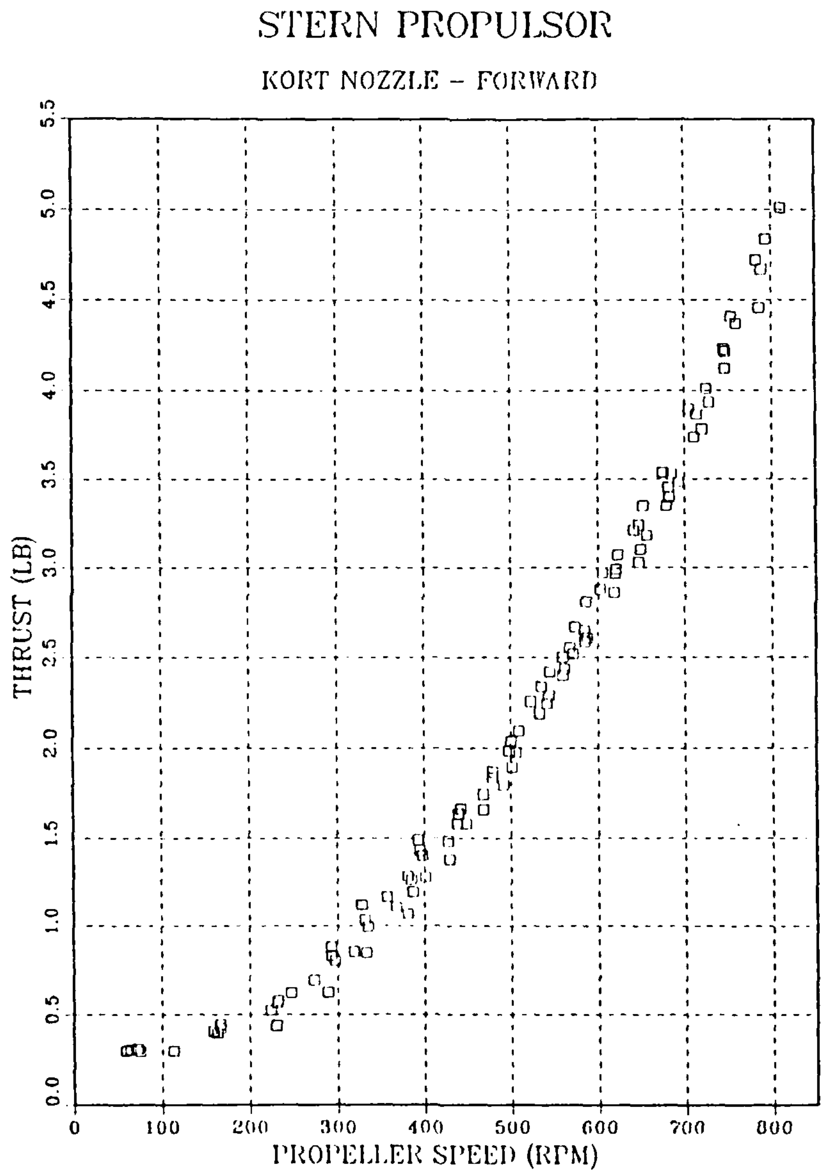

Figure 4.13. **Thrust vs. Rpm, Stern Propulsor (Kort Nozzle), Ahead Direction**

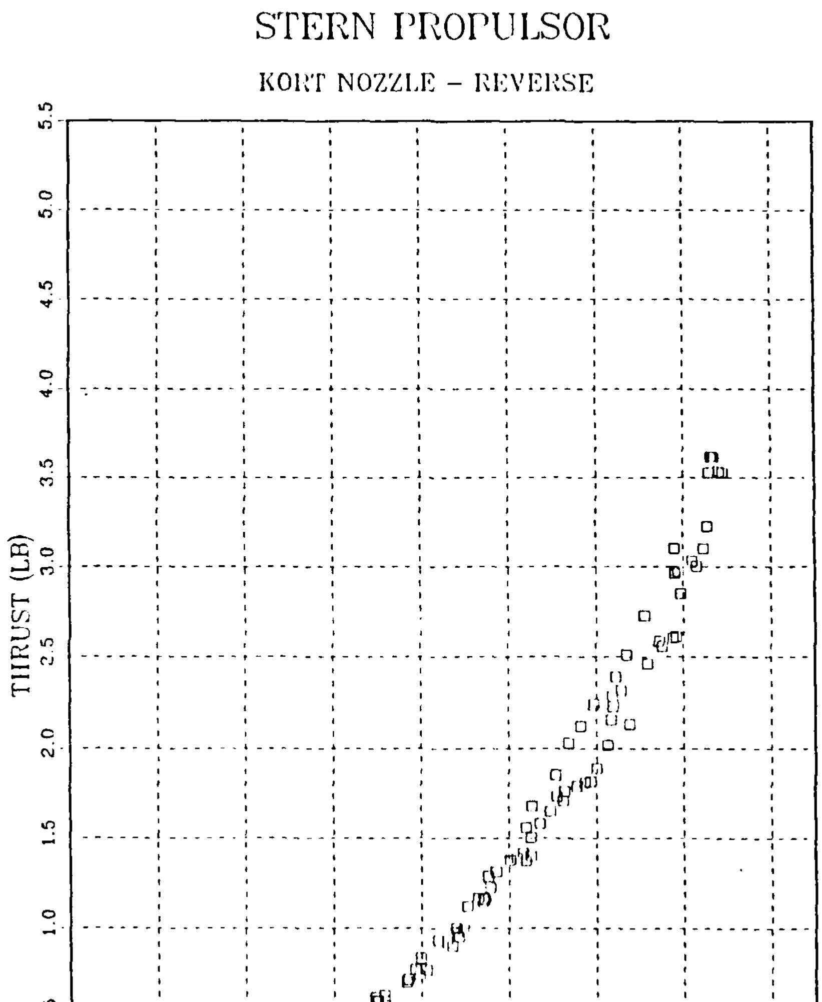

Figure 4.14. **Thrust vs. Rpm, Stern Propulsor (Kort Nozzle), Reverse Direction**

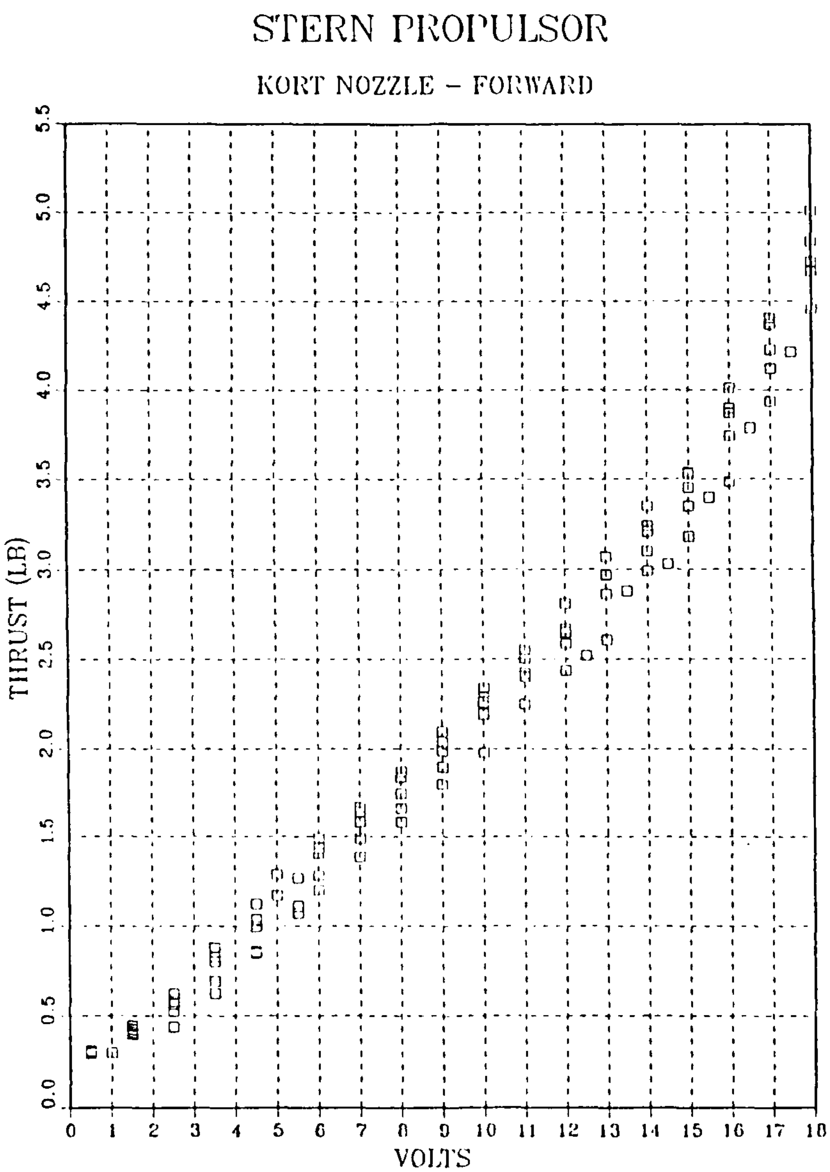

Figure 4.15. **Thrust vs. Voltage, Stern Propulsor (Kort Nozzle), Ahead Direction**

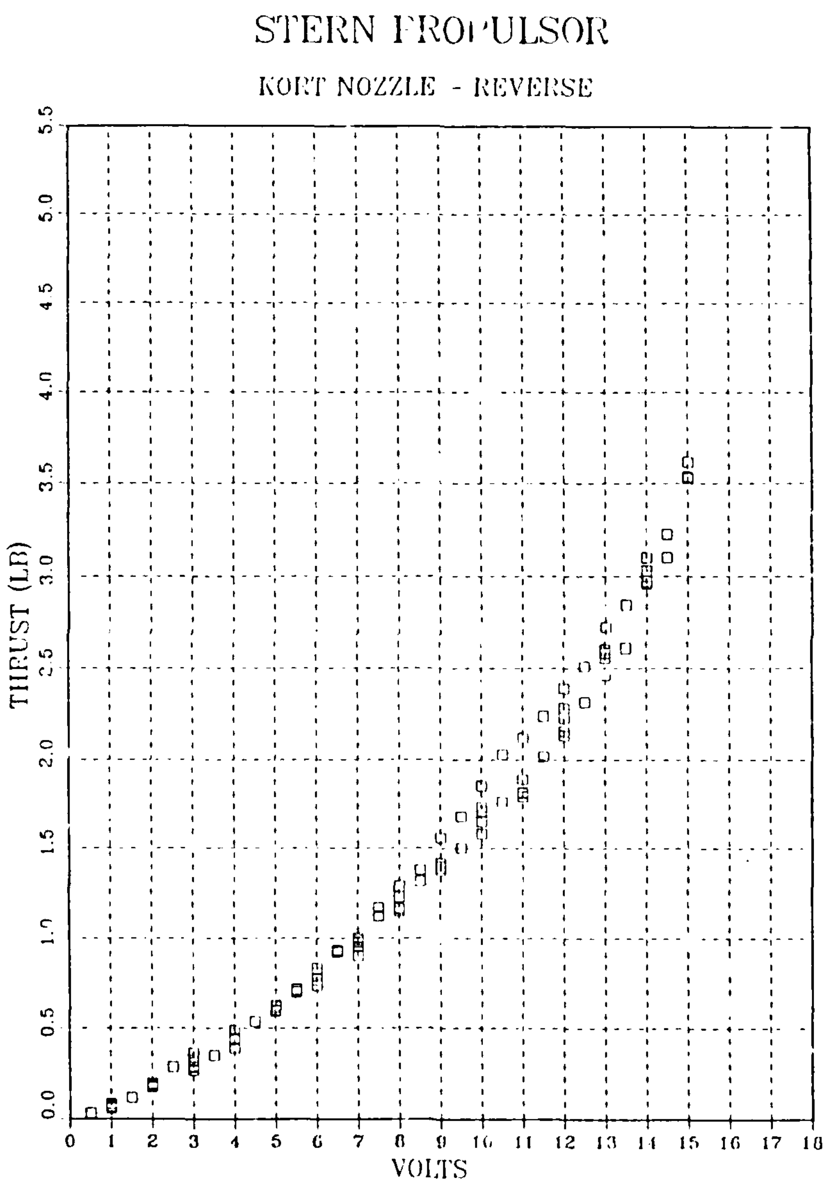

Figure 4.16. **Thrust vs. Voltage, Stern Propulsor (Kort Nozzle), Reverse Direction**

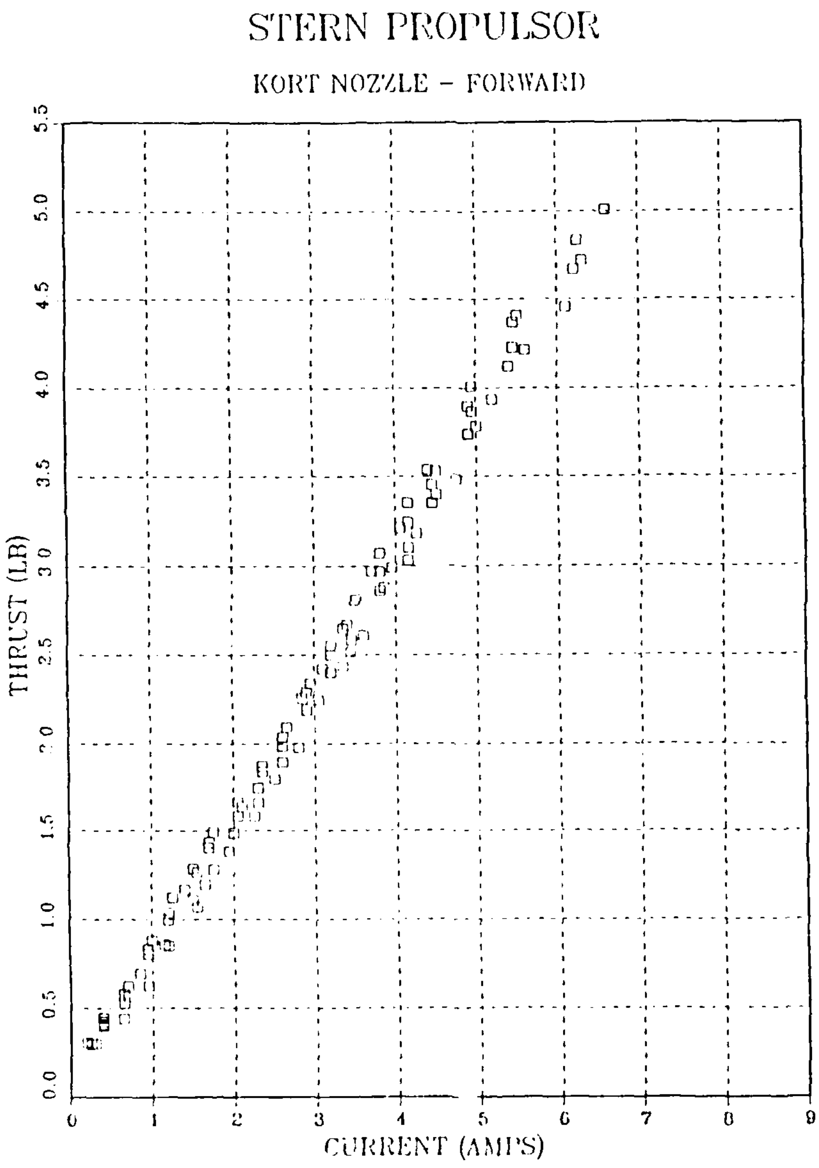

Figure 4.17. **Thrust vs. Current, Stern Propulsor (Kort Nozzle), Ahead Direction**

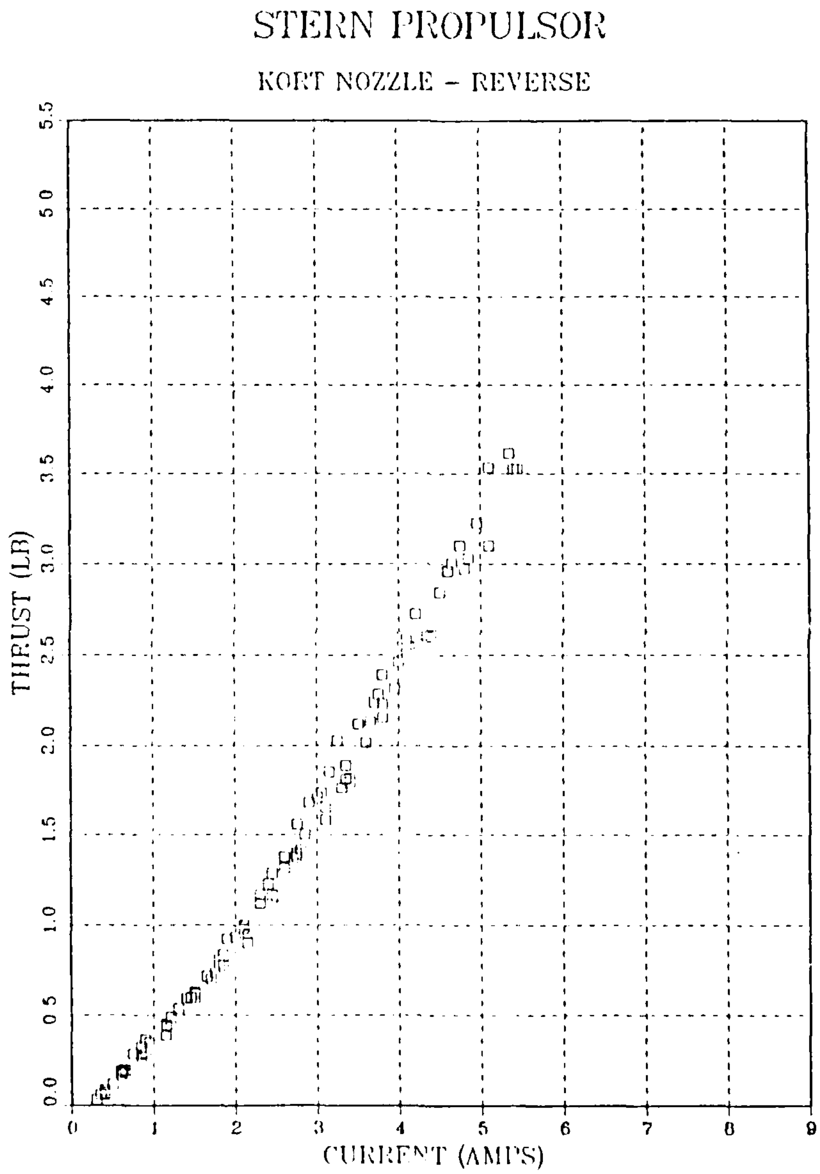

Figure 4.18. **Thrust vs. Current, Stern Propulsor (Kort Nozzle), Reverse Direction**

nozzle further reduce the power requirements for cruise propulsion as well as prolong motor life. In addition, the increased thrust capability at the upper end of the motor's operating range significantly increases the vehicle's acceleration/deceleration capability.

B. LATERAL THRUSTER

An analysis of the data derived from the testing of the tunnel thrusters (specifically, Figures 4.19 and 4.20), shows that the thruster design using the geared power transmission method succeeded in producing the goal of one pound of thrust in each direction. There is, however, a large variation in the data for a specific impeller speed. This spread is felt to be due primarily to a lack of satisfactory bearing material on the shafting of the thruster. The grease used to lubricate the shafts proved unsatisfactory after only a quarter hour of total run time and had to be reapplied twice in order to obtain the data illustrated. The test was a success, however, in that the design was proven to produce the requisite thrust at a power level (84 watts) that the motors should be capable of maintaining for long periods of time. The variance of thrust with voltage and current applied is shown in Figures 4.21 through 4.24. In addition, the devices produce thrust in varying amounts throughout the operating range of the motors, not merely an "all or nothing" response, and should be controllable.

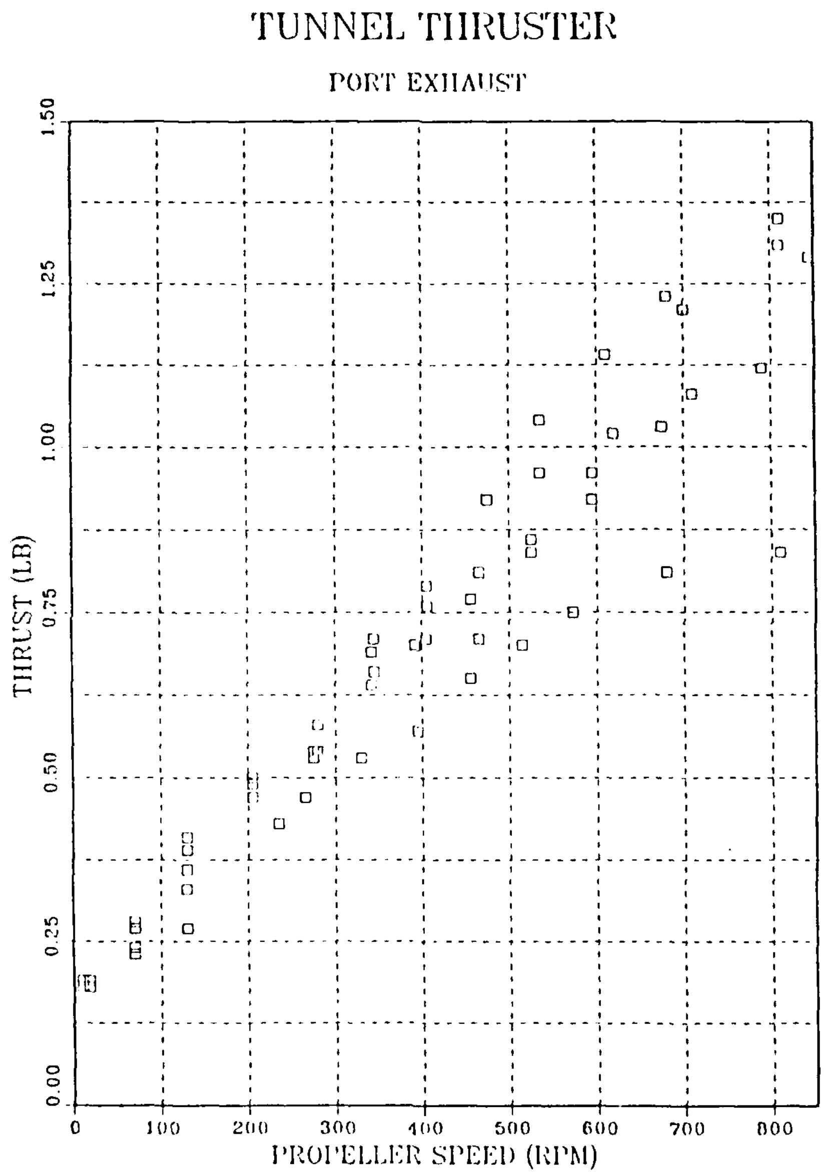

Figure 4.19. **Thrust vs. Rpm, Tunnel Thruster, Port Exhaust**

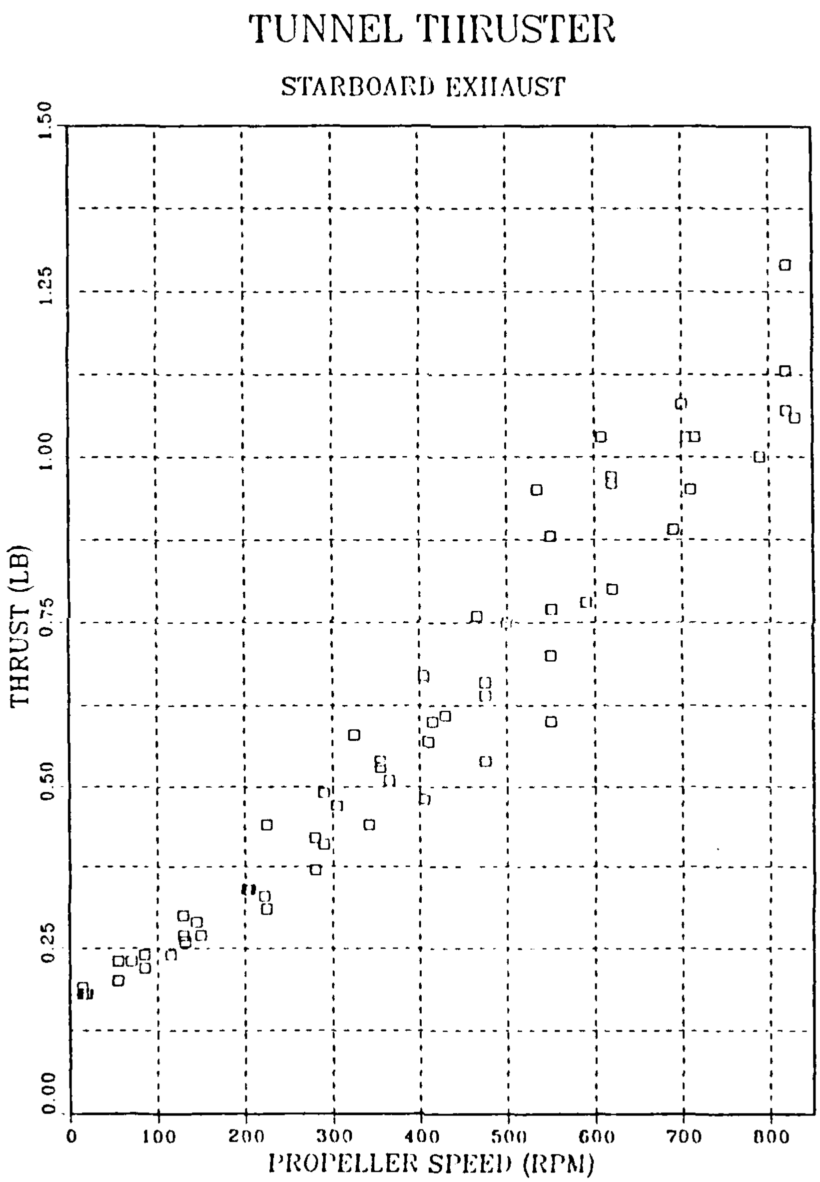

Figure 4.20. **Thrust vs. Rpm, Tunnel Thruster, Starboard Exhaust**

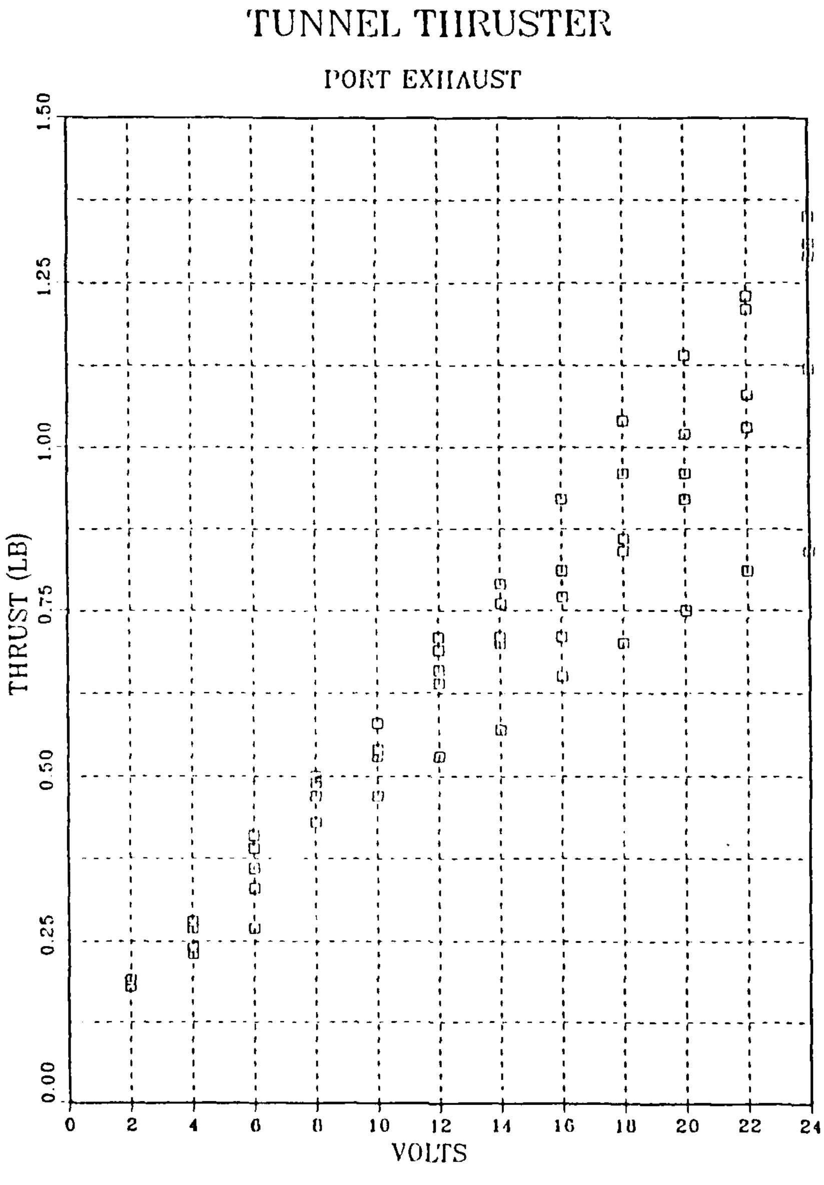

Figure 4.21. **Thrust vs. Voltage, Tunnel Thruster, Port Exhaust**

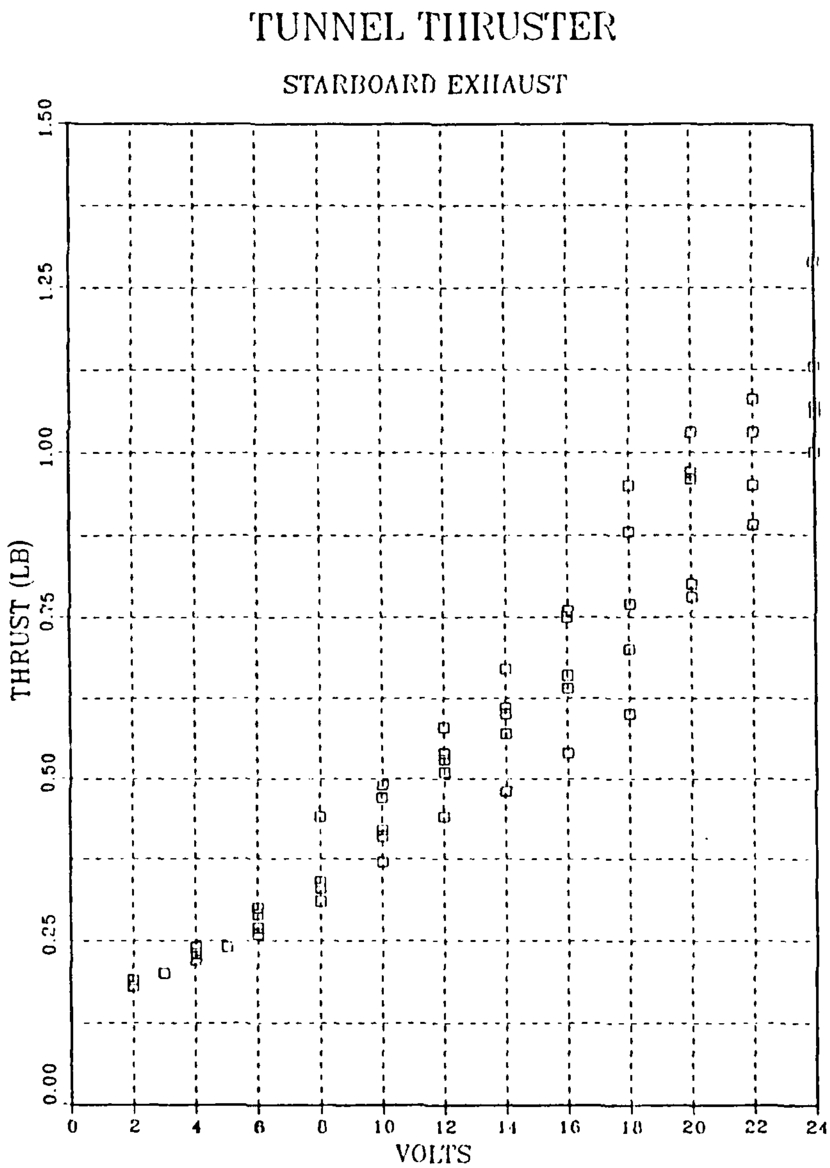

Figure 4.22. **Thrust vs. Voltage, Tunnel Thruster, Starboard Exhaust**

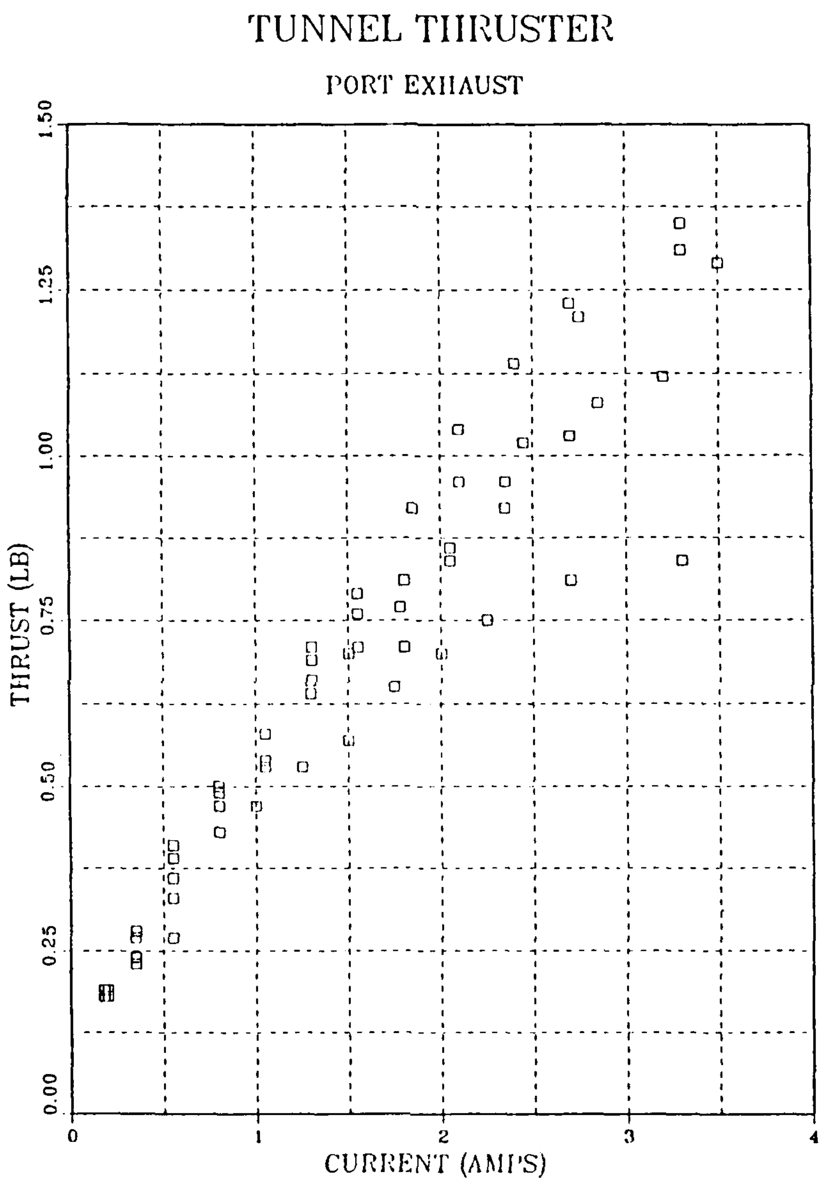

Figure 4.23. **Thrust vs. Current, Tunnel Thruster, Port Exhaust**

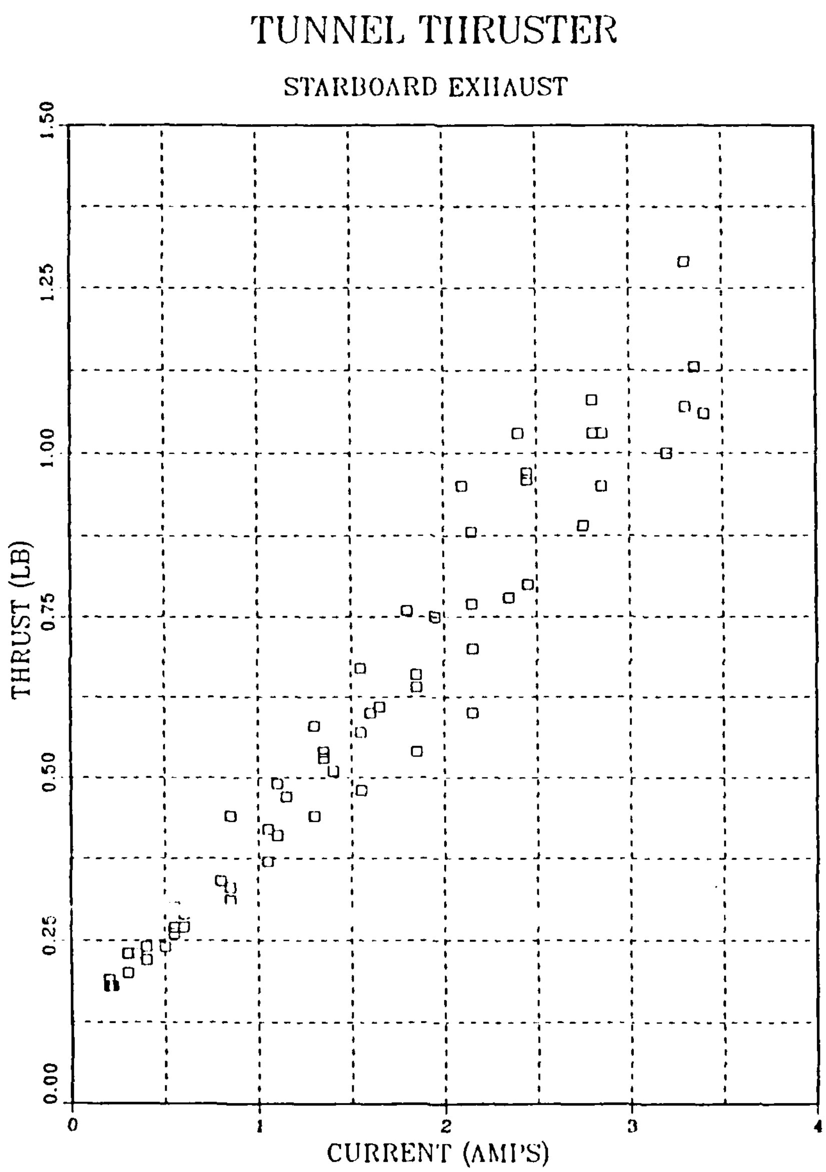

Figure 4.24. **Thrust vs. Current, Tunnel Thruster, Starboard Exhaust**

C. COMPARISON OF RESULTS WITH THEORY

Although work output by a propeller becomes zero at zero propeller advance, thrust is still produced, as evidenced by the testing results presented. Several figures of merit have been devised to quantitatively measure the efficiency of a propulsor in the static condition, with the most commonly used being the static-merit coefficient C, as discussed in Chapter II [Ref. 6]. Table 4.1 lists values of the merit coefficient for the four AUV II propulsion conditions tested and contrasts them with coefficients representative of those obtained in industry with large marine propulsion devices. Although the propulsors tested produced the design levels of thrust in packages that will fit inside the AUV, they do not compare well with large thrusters being produced by industry.

TABLE 4.1

COMPARISON OF STATIC MERIT COEFFICIENT C

Propulsion Type	**C**
Experimental	
Open Propeller, Single Motor	0.171
Kort Nozzle	0.347
Tunnel Thruster	0.073
Commercial	
Open Propellers	0.55–0.65
Kort Nozzles	1.4–1.6
Tunnel Thrusters	0.68–0.82
DSRV Tunnel Thrusters	
Initial Design	0.87
Final Design	1.46

An additional contrast is offered by Figure 4.25 [Ref. 13], which is a plot of thrust per horsepower versus horsepower per propeller area, with the static merit coefficient plotted for each of the ideal cases, as discussed in Chapter II. It can be seen that, as previously stated, the static merit coefficients of the AUV II propulsors are much less than those of the large marine thrusters. In addition, it depicts the significant difference in the horsepower per area ratios, being 2 hp/ft^2 or less for the AUV units, compared to a range of 5 to 100 hp/ft^2 for the large devices. The specific reason for the difference is not known. It is believed that, because of their great power, the larger thrusters are less susceptible to frictional losses associated with sealing mechanisms, such as bearings and stuffing tubes. The frictional forces generated in these mechanisms comprise only a small fraction of the power produced by the prime movers of the larger propulsion devices, while it may be a *very large fraction of the power of the smaller devices*.

Figure 4.25 also shows, however, that even if the power-per-area ratio of the AUV devices cannot be improved, the static merit coefficients *can*, by increasing the thrust-per-power ratio through increases in efficiency. Some of these improvements have already been discussed. Improvements on the installation of a Kort nozzle include (1) additional machining of the propeller blades and nozzle wall to reduce tip clearances to an absolute minimum, (2) a more exacting airfoil shape in the nozzle entrance, and (3) a shift to a Kaplan-type propeller, all of which could increase thrust available from the stern propulsor. Improvements

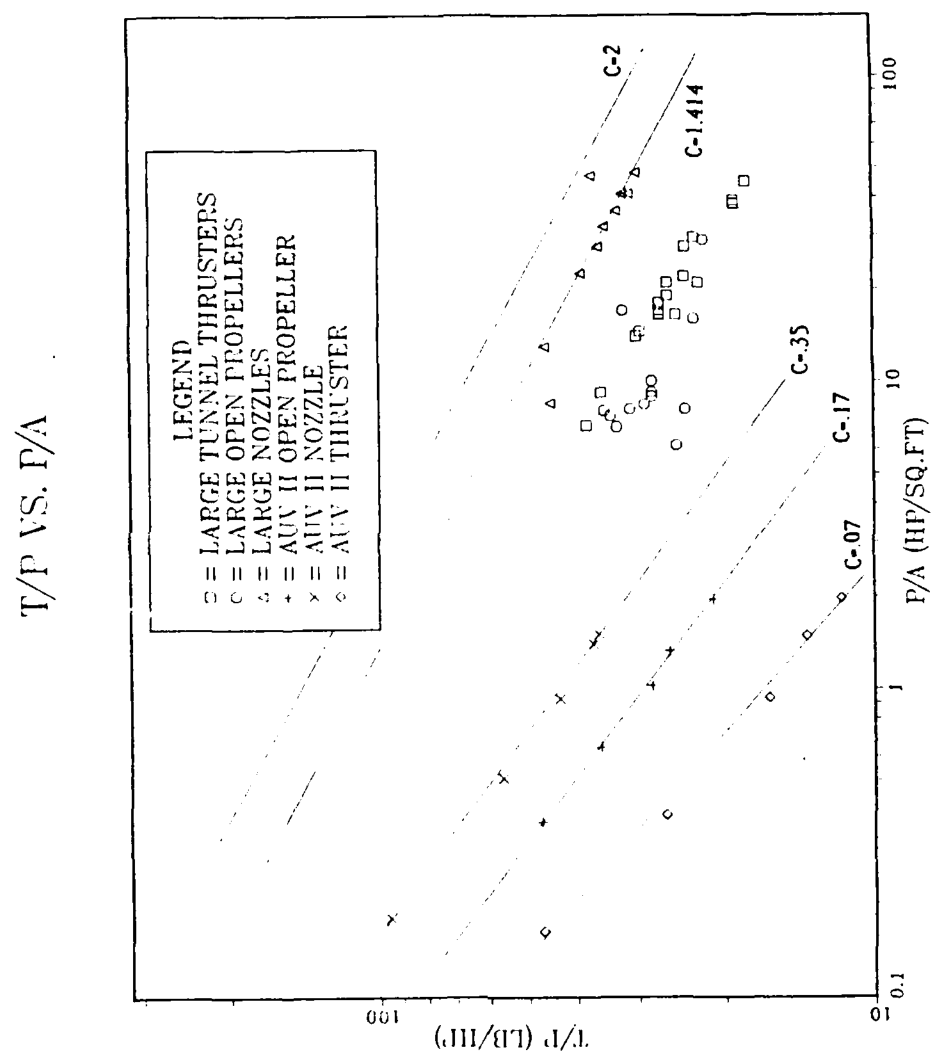

Figure 4.25. **Thrust Per Horsepower vs. Horsepower Per Propeller Area**

for the tunnel thrusters include (1) addition of the rounded lip on the tunnel entrances, which has been shown experimentally to increase thrust by 10 percent; (2) the installation of improved bearings to reduce the power transmission resistance; and (3) a more faired installation of the impeller blades to the supporting struts, increasing the flow efficiency of the impeller [Ref. 6].

V. VEHICLE PERFORMANCE SIMULATION

Using the results of the testing with the stern propulsion system, simulations were run to obtain an idea of actual vehicle performance in the longitudinal direction. The simulation program, consisting of a non-linear dynamic model of the vehicle coupled with a sliding-mode control scheme, was written by David Marco [Ref. 11]. Using characteristics of the propulsors determined from a graphical analysis of the data, approximations of acceleration, deceleration, and maximum speed capabilities of AUV II were estimated.

A. MATHEMATICAL MODEL

The nonlinear equations of motion used in the simulation were derived from the equations for the Mark IX Swimmer Delivery Vehicle (SDV), the basic shape used for both AUVs I and II [Ref. 14]. The dimensional components of the equations were scaled from the original 17-foot length of the SDV to the approximately six-foot length of AUV II. The values for nondimensional hydrodynamic coefficients were left constant and scaled for the dimensions planned for AUV II.

B. INCORPORATION OF EXPERIMENTAL DATA

The experimental data derived from propulsion testing was incorporated into the simulation through the "propulsion coefficient" term K_T in the equations of motion. The longitudinal equation of motion included

the propulsion term X'_{prop} to account for the net propulsive force of the propellers, where:

$$X'_{prop} = C_{D_0}\left[\eta|\eta| - 1\right] \tag{5.1}$$

$$\eta = \frac{U_{com}}{U} \tag{5.2}$$

$$U_{com} = \text{command forward speed (ft / sec)}$$

$$C_{D_0} = 0.00385 + 1.296 \times 10^{-17}\left(R_\ell - 1.2 \times 10^7\right)^2 \tag{5.3}$$

For the simplified case where all velocities with the exception of the longitudinal are zero, the longitudinal equation of motion reduced to:

$$\text{FORCE} = \tfrac{1}{2}\rho\ell^2 C_{D_0} U_{com}|U_{com}| - \tfrac{1}{2}\rho\ell^2 C_{D_0} U|U| \tag{5.4}$$

or:

$$F_{DRIVE} = \tfrac{1}{2}\rho\ell^2 (K_T)^2 n|n| \tag{5.5}$$

with:

$$K_T = \frac{U_{com}}{U}, \quad n = \text{propeller rpm}$$

The results of the tests with the large motors, both with and without Kort nozzles, showed that the thrust was proportional to the square of the rotational speed of the propeller:

$$F_{STATIC} = 2\alpha n|n| \tag{5.6}$$

The values of K_T to be used in the simulation were then obtained through the relation:

$$K_T = 2\left[\frac{\alpha}{\rho \ell^2 C_{D_0}}\right]^{\frac{1}{2}} \tag{5.7}$$

α	= experimental coefficient	ℓ	= 6 feet
ρ	= 1.94 slug/ft^3	$\left(C_{D_0}\right)_{U=0}$	= .005716

Table 5.1 lists the propulsion coefficients calculated for each propulsion arrangement.

TABLE 5.1

PROPULSION COEFFICIENT K_T

Propulsion Condition	**K_T**
Forward Direction, No Nozzle	0.00792
Reverse Direction, No Nozzle	0.00708
Forward Direction, With Nozzle	0.00830
Reverse Direction, With Nozzle	0.00729

C. PERFORMANCE OF MODEL

A variety of vehicle profiles were run with the simulation, both to verify the benefits of the Kort nozzle arrangement and to gain an idea of the performance to be expected of the actual vehicle. A data summary of the runs is presented i ı Table 5.2

TABLE 5.2

COMPILATION OF SIMULATION RESULTS

Condition	Open Propeller	Propeller/Nozzle
Maximum Acceleration	0.52 ft/sec^2	0.56 ft/sec^2
Maximum Deceleration	0.50 ft/sec^2	0.53 ft/sec^2
Maximum Cruise Speed	6.0 ft/sec	6.5 ft/sec
Propeller Speed for AUV @ 2 ft/sec	220 rpm	210 rpm

For the simulation, the maximum propeller speed available was considered to be 800 rpm in that, during testing at maximum voltage, the electric motor in a "warmed-up" condition settled to that value as a steady state.

In the simulation, the vehicle was capable of an acceleration and deceleration of approximately 0.5 feet per (second)^2 and a cruise speed of approximately six feet per second. Figure 5.1 depicts a sample profile used in the simulation: (1) an acceleration from rest to a speed of approximately 2.6 feet per second, (2) cruise at a steady speed for 30 seconds, and (3) a deceleration to a complete stop. Figure 5.2 shows the propeller speed commanded by the control algorithm to execute the profile shown

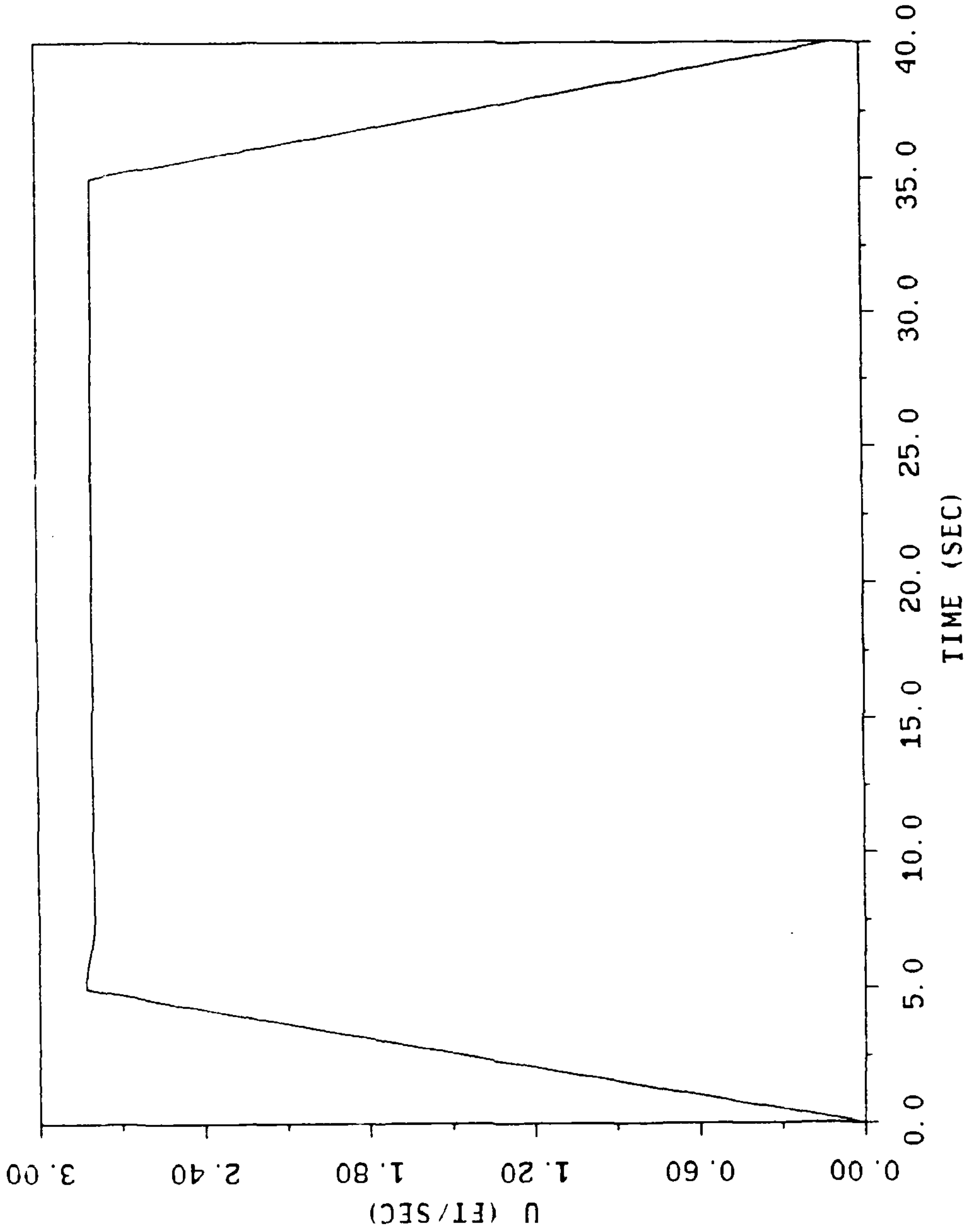

Figure 5.1. **Vehicle Speed vs. Time for Sample Simulation Profile**

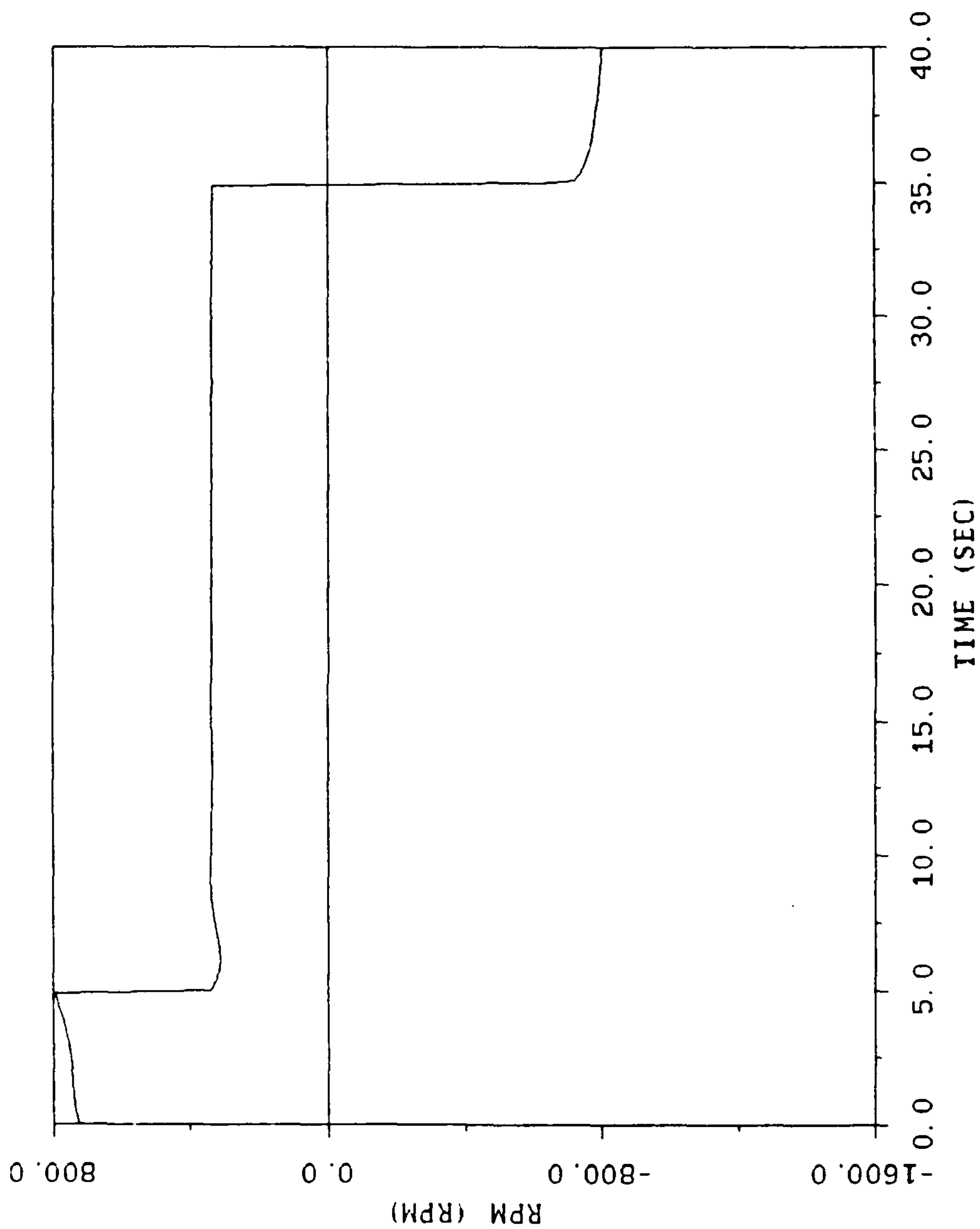

Figure 5.2. **Propeller Speed vs. Time for Sample Simulation Profile**

in Figure 5.1, with the maximum speed used in both acceleration and deceleration of the vehicle being approximately 800 rpm. Finally, Figure 5.3 shows the associated plot of distance travelled per unit time for the sample run. As the total distance was less than the NPS pool length, such a run could be used in initial vehicle testing. Neither the test data nor the simulation, however, took into account the reduction of propeller thrust with an increase in forward speed. Despite this, the simulation results do demonstrate some other points: (1) the propellers are more efficient in the ahead direction than they are in the astern direction, as shown by the higher propeller speed necessary to slow from a specific vehicle velocity than was necessary to achieve that velocity, and (2) the addition of Kort nozzles allows the propellers to turn at between 15 to 30 rpm less for a specific vehicle velocity, an attribute that allows reduced power levels (and battery consumption) for cruising as well as increased acceleration/deceleration capabilities over open propellers. In addition, even with a significant reduction in the performance figures shown in the simulation, the actual vehicle should perform much better than the original design values of two feet per second cruise speed and .167 feet per $(\text{second})^2$ deceleration.

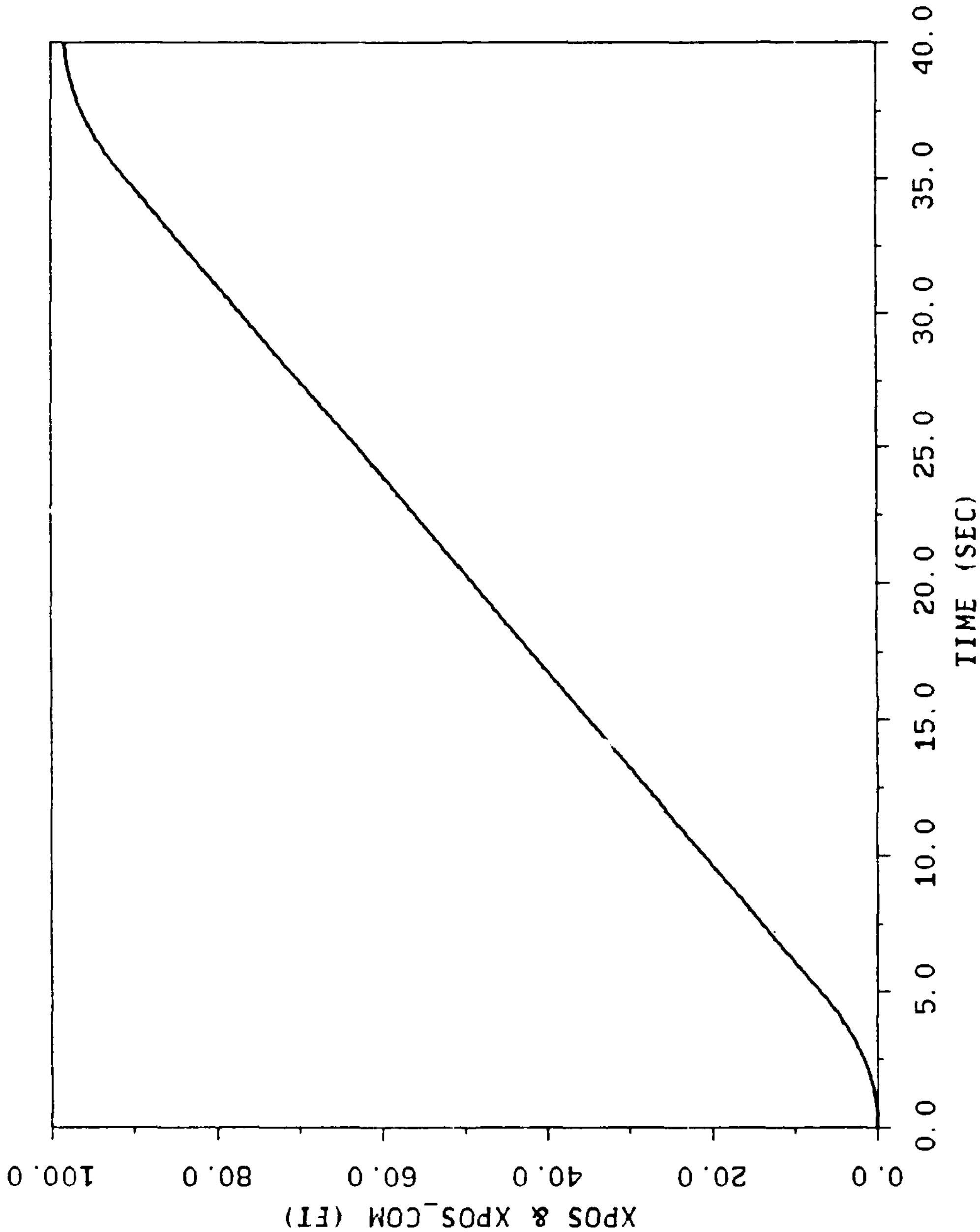

Figure 5.3. **Distance Travelled vs. Time for Sample Simulation Profile**

VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

This work has presented the procedures for the static testing of small propulsion devices, the results obtained from the testing of propulsors designed specifically for the NPS AUV II, and the results of the application of the experimental data to a computer simulation of the vehicle to obtain preliminary performance estimates. Several conclusions may be drawn from this effort:

1. Despite the designs not being optimal in terms of efficiency, both the longitudinal and lateral thrusters met the design goal of producing one pound of thrust in the static condition.

2. Preliminary static testing of new propulsion designs is extremely important in order to insure the success of a vehicle design. Without such testing, especially at an early vehicle design stage, both time and material can be wasted.

3. As expected, thrust for both the longitudinal and the lateral propulsors was shown to vary as the square of propeller speed as well as linearly with motor current. Due to its linear variation with thrust, motor current may be a better propulsion control parameter than propeller speed.

4. The addition of a Kort nozzle to an open propeller can provide a significant increase in the static thrust produced, even without an optimized nozzle design.

5. As expected, for the longitudinal case, propeller performance is worse in the reverse direction than it is in the ahead direction.

6. The efficiencies of the AUV II propulsion devices are significantly less than those of larger marine units, at least as compared via the static merit coefficient C. The reasons for the difference are not specifically known and warrant further study.

7. In order to properly test propulsion devices in the static condition, either a test facility should be constructed to preclude the formation

of flow discrepancies or some method should be employed to reliably measure the flow's characteristics so that the effect on the final test result may be quantified.

B. RECOMMENDATIONS

Additional research is recommended as follows:

1. Perform additional performance testing of improved propulsor designs to determine whether the resulting increase in thrust warrants application of the improvements to AUV II. Improvements to be tested include an optimized Kort nozzle design for the stern propulsor as well as exit lip modifications for the tunnel thruster design.

2. Conduct additional testing to determine the performance characteristics of the propulsors at a variety of forward speeds. The results of such tests would aid the design of a propulsion control system as well as help to determine the cruise speed capabilities of AUV II prior to actual vehicle tests.

3. Conduct additional testing to determine the dynamic control response of the AUV propulsors using a rigid test fixture. The semirigid test fixture used in support of this thesis damped the response of the propulsors to control input. Any lags in propulsion system response to a control input need to be determined in order to be incorporated into the design of the propulsion control algorithm.

4. Incorporate the experimental tunnel thruster data into an appropriate dynamic computer model of the AUV to predict the hovering and low-speed characteristics of the vehicle.

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